NAVAL POSTGRADUATE SCHOOL
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THESIS

VARIATIONS IN COASTAL CIRCULATION
OFF CENTRAL CALIFORNIA,
SPRING-SUMMER 1993, 1994, 1995

by

Heather A. Parker

December 1996

Thesis Advisors: Newell Garfield
Franklin B. Schwing

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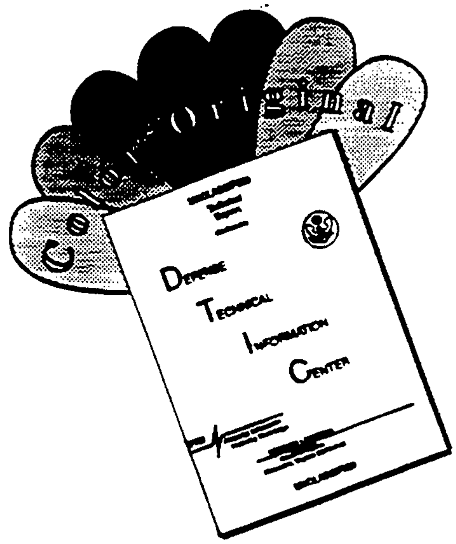

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In situ measurements of hydrographic, wind and Acoustic Doppler Current Profiler (ADCP) data, along with satellite imagery, were collected off central California during the upwelling season of three successive years, 1993, 1994 and 1995. The survey was conducted three times in the late spring of each year within 75 km of the coastline from Point Reyes south to Cypress Point, along a region of irregular coastline and bathymetry. The upwelling circulation was found to be distinct from the California Current System and unlike circulation defined in recent conceptual models for this region. Persistent or recurring circulation features were observed throughout the upwelling season that acted as dynamic boundaries to this system. A varied response by upwelling centers in this region to a fairly uniform wind field was also observed. Water upwelled within this system is considered to recirculate and mix, retained within the system for a relatively long period of time. This long retention period of upwelled water is thought to promote the high productivity associated with coastal upwelling. The circulation patterns found in this region, and the dynamic boundaries to the principal equatorward current may represent upwelling circulation at multiple locations in this and in other eastern boundary current systems, inshore of the principal equatorward current.

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VARIATIONS IN COASTAL CIRCULATION OFF CENTRAL CALIFORNIA, SPRING-SUMMER 1993, 1994, 1995

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ABSTRACT

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I. INTRODUCTION

Coastal circulation off California during the spring-summer season has been the focus of several major studies in recent years. Most of these studies, however, were concentrated north of Point Reyes and confined to one or two-year surveys, sampled only once. Since 1983, the annual National Marine Fisheries Service (NMFS) Juvenile Rockfish Survey has focused on collecting water property and velocity data in a high-resolution grid three times each spring-summer in the coastal area from Point Reyes south to Cypress Point. The purpose of this paper is to summarize the 1993 to 1995 velocity and water property data from these surveys and then compare these results with recent conceptual models and conventional theories regarding coastal circulation off northern and central California and in eastern boundary currents in general. The focus of this paper will be to summarize the spatial structure of circulation and water properties during the spring-summer off central California; describe variations in circulation and water properties on synoptic and interannual time scales; and assess the effects of the varying density structure on coastal circulation. Analysis of water types found near-surface will be compared with real-time current measurements of the circulation of these water types. Persistent or recurring flow features in this region, filaments, plumes and eddies, will be defined in the context of how they respond differently to a fairly-uniform wind field and how they establish a distinct nearshore system that appears to retain water upwelled within the system and thereby enhance the biological productivity of the region.

Data from the NMFS surveys show that during the upwelling season, circulation in this region is distinct from that in the California Current System. Persistent flow features act as dynamic boundaries in the nearshore region, retaining the regionally-distinct water types and inhibiting exchange with the California Current. The response to upwelling winds at two nearby upwelling centers was found to be quite different. This difference in upwelling response is seen to promote the development of distinct pockets of upwelled water, potentially resulting in a highly productive ecosystem.

II. BACKGROUND

Based on water temperature and the source of water types found in this region, three seasons are defined for central California coastal waters: upwelling, oceanic and the Davidson current (Breaker and Broenkow, 1994). The start of the highly productive upwelling season off central California is marked by the spring transition, a rapid progression to sustained northwesterly winds along the coast (Huyer et al., 1979; Strub et al., 1987; Lentz, 1987). Caused by steepened gradients between the North Pacific high pressure system and a thermal low over the southwestern United States, this transition results in persistent northwesterly winds along the west coast (Halliwell and Allen, 1984). As upwelling-favorable conditions commence, a marked drop in the coastal sea surface temperature (SST) accompanies a drop in coastal sea surface height within the short transition period, remaining throughout the duration of the upwelling season. Coastal circulation during the upwelling season is highly variable and difficult to quantify, and is driven primarily by the local wind field. As stated previously, this thesis will focus on the circulation characteristics during the upwelling season off central California.

Three major studies in the last decade, the Coastal Ocean Dynamics Experiment (CODE), the Northern California Coastal Circulation Study (NCCCS), and the Coastal Transition Zone (CTZ) program have examined and provided much insight into the dynamics of the spring-summer circulation off northern and central California.

CODE was designed to determine the dynamics of wind-driven flow over the continental shelf during the upwelling season off northern California (Beardsley and Lentz, 1987). This project involved measurements from a series of moored arrays spaced with a relatively small alongshore length scale (O(30 km)). A significant finding from this work was that currents, water properties and hydrostatic pressure during the upwelling season all have alongshore length scales longer than the cross-shelf direction (Huyer and Kosro, 1987; Kosro, 1987; Lentz, 1987; Strub et al., 1987). These findings, however, reflect shelf dynamics over relatively homogenous bathymetry and coastal topography, compared with the central California shelf region,

where sharp coastal promontories and significant changes in bottom topography are more exaggerated. The CODE study generally defined the upwelling state in terms of a relatively static, two-dimensional system (Lentz, 1987) that does not appear to adequately describe the observations of the upwelling state indigenous to the central California shelf region.

As a follow-up to the CODE experiment, NCCCS set out to further describe alongshore and temporal variations in wind-driven circulation over the continental shelf and slope during the upwelling season (Largier et al., 1993). The survey consisted of moored instruments between San Francisco and the Oregon border, within 30 km of the coast, with spacing between instruments that resolved longer length and width scales than CODE. Alongshore variations of temperature and currents were resolved on three distinct spatial scales: (1) large-scale changes related to the large-scale wind field, (2) mesoscale changes related to recurring mesoscale oceanic features, such as eddies and meanders moving on and offshore; and (3) small-scale changes associated with local wind fields and variations in topography. Congruent with results from CODE, circulation variance was found not only to be strongly correlated with synoptic local winds, but with longer scale changes in larger scale wind patterns and to variations in remote wind stress through the mechanism of an alongshore pressure gradient. The seasonal development of this pressure gradient was thought to modulate the synoptic current response to winds. Persistent equatorward currents, observed on several occasions despite local episodic wind relaxation events, were attributed to forcing by onshore advection of deep ocean mesoscale anticyclonic eddies. Cross-shore currents varied alongshore in their response to local winds. These variations were considered the result of strong wind fluctuations resulting from changes in coastline orientation. The NCCCS results describe upwelling to be more of a three-dimensional response to wind forcing on the shelf and slope than defined in previous studies.

The CTZ program, a multi-disciplinary survey performed in 1987 and 1988, made further progress in resolving the dynamics of the interactions between the California Current and coastal waters during the upwelling season off the coast of

northern California (Brink and Cowles, 1991). After the spring transition, persistent equatorward wind stress establishes an upwelling state along the coast. As coastal waters are advected offshore, cooler, more saline water is vertically advected to replace it, setting up an offshore increase in sea surface slope (Kosro et al., 1991). Persistent upwelling-favorable conditions cause the thin band of recently-upwelled water to widen along the coast. This band is separated from warmer, fresher offshore water by a frontal zone, whose gradients of temperature and salinity vary in steepness spatially and temporally (Kosro et al., 1991). Along this frontal zone, it is thought that an alongshore baroclinic current, or jet, develops and meanders on and offshore (Ramp et al., 1991). Brink et al. (1991), from analysis of long-term drifter data, suggest that the meanders of the alongshore baroclinic jet expand in the cross-shore direction with decreasing latitude. Due to processes not quite understood, this meandering jet becomes unstable and episodically forms eddies (Strub et al., 1991). Eddies on the order of 100 km diameter that develop inshore of this baroclinic jet are thought to entrain cold upwelled water and advect it seaward in the form of filaments. These filaments extend up to 250-300 km offshore, are on the order of 100 km wide, penetrating past 200 m depth and have a lifespan of about one month (Ramp et al., 1991).

Send et al. (1987) and Rosenfeld et al. (1994) qualified upwelling and relaxation states as distinct circulation and water property regimes, with a rapid transition period between the two. The Rosenfeld et al. study focused on Monterey Bay, where three persistent features were found during the upwelling season. First was the presence of warm and salty water inside the northern bight of Monterey Bay. Described in Graham et al. (1992) as an "upwelling shadow", this region is considered to be in the lee of upwelling-favorable winds. Weak vertical wind mixing, combined with increased surface heating, are thought to cause near-surface waters in the bight to have a warmer signal than nearby cold upwelled water. A second upwelling feature found by Rosenfeld et al. was an equatorward filament advecting cold water upwelled at the Pt. Año Neuvo upwelling center across the mouth of Monterey Bay. Rosenfeld et al. define an upwelling center as a site of intensified upwelling, usually at a coastal

point or cape. Satellite imagery correlated with in situ hydrographic measurements that revealed the Pt. Año Neuvo filament extending equatorward during persistent upwelling. During episodic relaxation from upwelling, circulation and water properties respond quickly to the change in wind forcing, displaying characteristics unique to relaxations. The third upwelling feature observed was the development of a warm, fresh anticyclonic eddy at the mouth of Monterey Bay upon the return of upwelling that immediately followed a relaxation event. The dynamics of its generation are still unknown, but may involve a change in the potential vorticity caused by offshore-tending filaments of upwelled water leaving both Pt. Año Neuvo to the north and Pt. Sur to the south.

The NMFS Pelagic Young-of-the-Year (YOY) Rockfish surveys were conducted in an area bounded by Point Reyes (38.17°N) to the north and Cypress Point (36.58°N) to the south, extending offshore approximately 75 km (Sakuma et al., 1994). The rich complexity of the coastal topography in this region distinguishes it from other sections of coastline along North America. Bathymetry in this region is diverse, including the Monterey Submarine canyon as well as several steep banks and seamounts. In addition to several coastal points that are sites of preferred upwelling, e.g., Pt. Reyes and Pt. Año Neuvo (Rosenfeld et al., 1994), San Francisco and Monterey Bays disrupt the coastline. Other physical systems at work in this region are significant fresh water input from San Francisco Bay and measurable contributions of solar insolation on surface waters in shallow shelf regions (Rosenfeld et al. 1994). The NMFS survey region is inshore of the coastal transition zone described by the CTZ collaborators, and south of the CODE and NCCCS study areas. The dynamics of upwelling circulation along the shelf and slope in this region are distinct, and represent a complex combination of the characteristics described to the north.

Despite all these studies, oceanographers still do not fully understand the processes leading to cross-shelf circulation. Available models do not adequately reproduce observed current variation. The NMFS study provides more insight into the processes that control coastal circulation during upwelling, and their relative importance. The objectives of this thesis are to describe the water types found in the

shelf and slope region off central California during the upwelling season and their circulation. The variability in the location, circulation and source of these water types will be described within an upwelling season and between upwelling seasons of different years in an attempt to better characterize the physical processes at work in this region.

III. EXPERIMENT DESIGN AND DATA PROCESSING

A. CRUISE DESIGN

The three annual cruises featured in this paper are part of a multi-year series of similar young-of-the-year (YOY) rockfish surveys conducted on the NOAA Ship David Starr Jordan (DSJ) each spring-summer since 1983 through the National Marine Fisheries Service's (NMFS) Southwest Fisheries Science Center (SWFSC). The data sampling routines consisted primarily of nighttime midwater trawls, set consecutively at 30 m depth for 15 minutes. Daytime operations focused on Conductivity-Temperature-Depth (CTD) casts at standard stations, usually to 200 m depth (Fig. 1). Three consecutive "sweeps", of roughly 10 days each, were performed for each annual cruise, the dates of each are defined Table 1. The survey grid is in an area bounded by Cypress Point (36.58°N) to the south and Pt. Reyes (38.17°N) to the north, and from the coast to approximately 75 km offshore (Fig. 1). A more complete description of cruise operations and data collection is in Sakuma et al. (1994).

Table 1. Sweep dates for the 1993 - 1995 NMFS YOY rockfish surveys.

Cruise	Sweep	Dates
1993	DSJ9307.1	13 MAY - 20 MAY
	DSJ9307.2	21 MAY - 28 MAY
	DSJ9307.3	03 JUNE - 10 JUNE
1994	DSJ9406.1	19 MAY - 26 MAY
	DSJ9406.2	27 MAY - 03 JUNE
	DSJ9406.3	11 JUNE - 19 JUNE
1995	DSJ9506.1	17 MAY - 26 MAY
	DSJ9506.2	27 MAY - 05 JUNE
	DSJ9506.3	08 JUNE - 19 JUNE

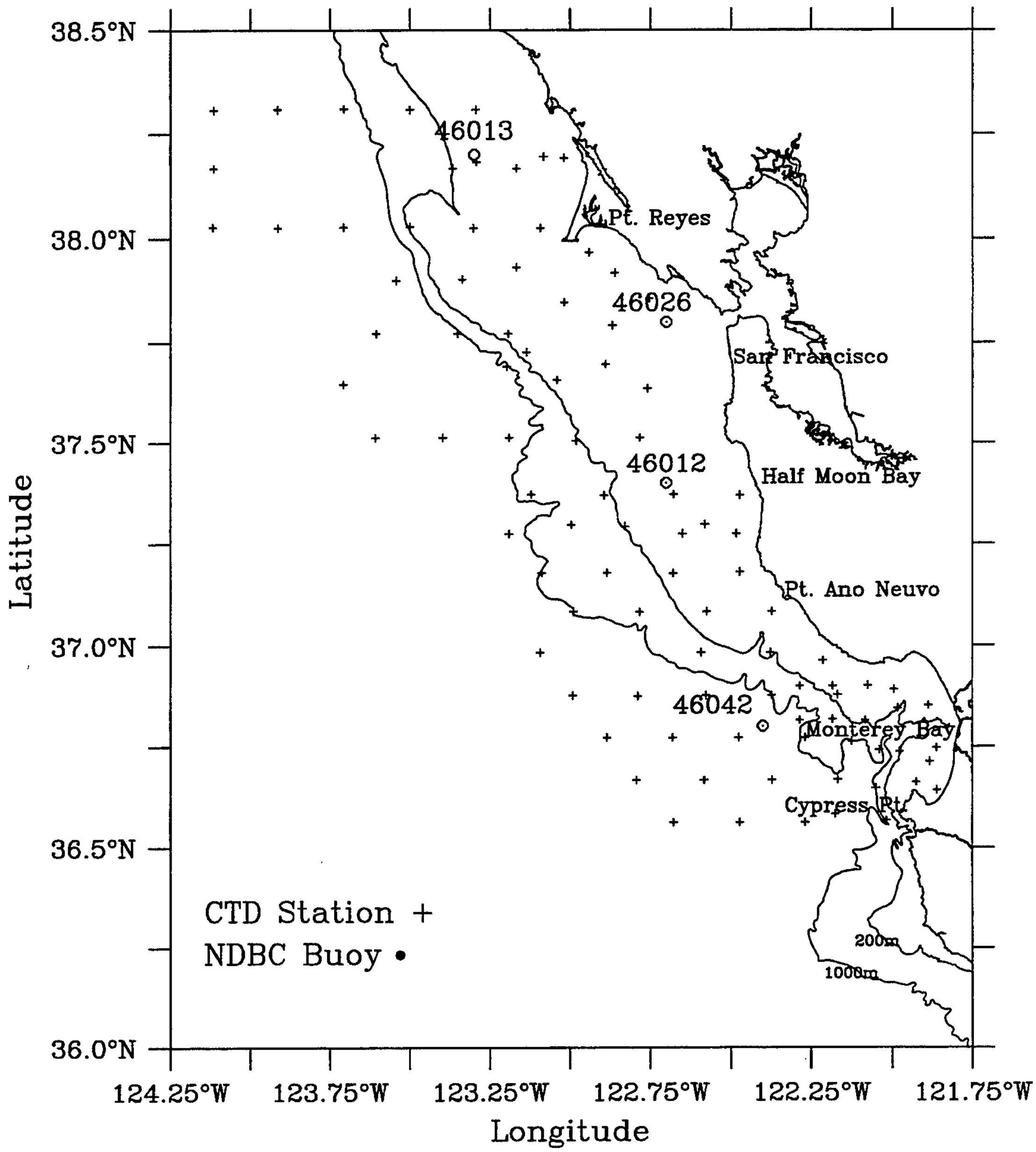

38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
124.25°W
123.75°W
123.25°W
122.75°W
122.25°W
121.75°W
Longitude
46013
Pt. Reyes
46026
San Francisco
46012
Half Moon Bay
Pt. Ano Neuvo
46042
Monterey Bay
Cypress Pt.
200m
1000m
CTD Station +
NDBC Buoy •

Figure 1

B. ADCP DATA PROCESSING

Acoustic Doppler Current Profiler (ADCP) data were collected with an RD Instruments 150 kHz, hull-mounted transducer on the NOAA Ship David Starr Jordan. The data acquisition software (DAS) was RDI's DAS version 2.48, and data were logged using a 386 PC. The data were collected in 64 depth bins, each 8 m deep, and averaged over 180 seconds per ensemble. The onboard Magnavox Global Positioning System provided navigation information to the DAS. Information from the Sperry Gyrocompass allowed the transformation of x-y coordinates to latitude and longitude coordinates. Because the first 4 m of the data were blanked and the depth of the transducer heads was 3 m, the 7-15 m bin provided the shallowest usable data.

A calibration run was conducted during each cruise to quantify the rotation and sensitivity errors. The rotation error (α) has two components: alignment error between the ship's centerline and the mounted instrument orientation, and gyrocompass error. The sensitivity errors (β), caused by errors in the beam geometry, are generally small but important to quantify. The computation of these errors was guided by the methods prescribed in Joyce (1989). The calibration coefficients for each cruise may be found in Table 2. The raw doppler data were rotated by α and multiplied by $1+\beta$ prior to processing. These data were then processed with a series of post-processing programs described in Jessen (1992) and Jessen et al. (1992).

The ADCP data are separated into individual sweeps, defined by the dates shown in Table 1. The three-minute water velocities for each sweep were then averaged over 5 km intervals to produce the vector maps presented in this document. Maps of total current field are presented at near-surface depth ranges (15-31 m) for selected sweeps of DSJ9307, DSJ9406, DSJ9506. The velocity vectors are overlaid on the 10 m temperature field, shaded to the temperature key. The arrows represent current vectors pointing in the direction the current is flowing. The length of the vector represents current magnitude, scaled to the 50 cm/s vector displayed in the plot's legend.

Table 2. Values of the Rotation (α) and Sensitivity (β) Errors for each cruise.

Cruise	Rotation Error (α)	Sensitivity Error ($1+\beta$)
DSJ9307	1.6	1
DSJ9406	1.377	1
DSJ9506	2.189	1

C. CTD DATA PROCESSING

All CTD (Conductivity Temperature Depth) data collected from the rockfish surveys presented here were collected with two Sea-Bird Electronics, Inc., SEACAT-SBE-19 profilers. These particular units were rated to 600 m depth and contained 256K of memory.

The profilers were deployed at the end of a hydrographic winch cable while the vessel was stopped. The profilers were first suspended just beneath the surface for two minutes to allow the conductivity and temperature sensors to equilibrate. An average descent rate of 45 m/minute was then used to deploy the instrument to 520 m, or 10 m from the bottom if the depth was less than 500 m. Data from the downcast were used for this study. For a more detailed description of processing of the raw CTD data, refer to Sakuma et al. (1994).

Selected horizontal maps of temperature (°C) and salinity are presented at 10 m depth, for each annual survey, by sweep. Temperature is shaded, referenced with a key, and salinity contours are overlaid. Maps of the depth and temperature along the 26.2 potential density (σ_θ) surface are also presented for selected sweeps of each year. The depth of the 26.2 σ_θ surface is shaded, overlaid with contours of temperature along that surface.

D. METEOROLOGICAL DATA

Wind time series were obtained from four National Data Buoy Center (NDBC) moored meteorological buoys within the survey area. The buoy identification numbers and locations are as follows: 46013 (Bodega Bay; 38.20°N, 123.30°W), 46026 (Farallones; 37.80°N, 122.70°W), 46012 (Half Moon Bay; 37.40°N, 122.70°W) and 46042 (Monterey Bay; 36.80°N, 122.40°W). Daily averages of surface wind were calculated.. Plots of daily mean winds for the first 180 days of each year are presented for 1993, 1994 and 1995. The stick vector points in the direction of the wind and its length represents wind speed, scaled to the 50 cm/s vector displayed in the plot's legend.

E. SEA SURFACE TEMPERATURE DATA FROM AVHRR SATELLITE IMAGERY

A detailed description of the AVHRR data procedures can be found in Sakuma et al. (1995). Sea surface temperatures along the central California coast were determined from radiances sensed by channel 4 of the NOAA-11 polar orbiting satellite. Images represent a single pass the afternoon of the date listed, in local time. Locations of sampling and CTD stations were overlaid on the image. The false color scale used ranges from 8 to 18 °C. Clouds and/or fog appear as black, while coastal upwelling appears as dark blue to black.

IV. OBSERVATIONS

A. SPRING-SUMMER 1993

During the upwelling season of 1993 a tropical El Niño-Southern Oscillation event (ENSO), determined by the NOAA/NMFS *El Niño Watch Advisory* (issues 93-05, 93-06, CoastWatch, SWFSC, La Jolla, CA), was measured off central California as a 1-3°C positive sea surface temperature (SST) anomaly. Northwesterly winds dominated the wind field along central California for two months prior to the DSJ9307 survey (Fig. 2). This pattern reversed on the second day of the first sweep and winds blew predominantly from the southeast, i.e.,downwelling-favorable, for the next several weeks.

Although local winds were from the southeast through most of Sweep 1, near-surface temperature and salinity fields retained characteristics of an upwelling state (Fig. 3). Cooler and more saline water was found along the coast, particularly near coastal points or promontories. Warmer and fresher frontal water, a mixture of upwelled water and water entrained from the eastern edge of the California Current, was separated from the cold, saline recently-upwelled water by relatively steep coastally-aligned gradients. An area of steep gradients of temperature and particularly salinity extended offshore and equatorward near Pt. Reyes, conditions characteristic of an offshore-flowing upwelling jet (Ramp et al., 1991).

By the second sweep, near-surface temperature and salinity fields more clearly reflected the persistent poleward winds (Fig. 4). Gradients of these properties defined a large warm, fresh feature between 36.75°N and 38.00°N. This feature was approximately 90 km long and 50 km wide, extended to 100 m depth, and near the surface was warmer than 14.0°C with salinity less than 32.8. It appears to have moved south from Sweep 1, to just offshore of Half Moon Bay. Near-surface temperatures experienced a 1.0°-1.5°C increase from Sweep 1 throughout the area. The range of near-surface salinity did not shift dramatically, although water more saline than 33.4 was found only near Monterey Bay, while water off Pt. Reyes had a

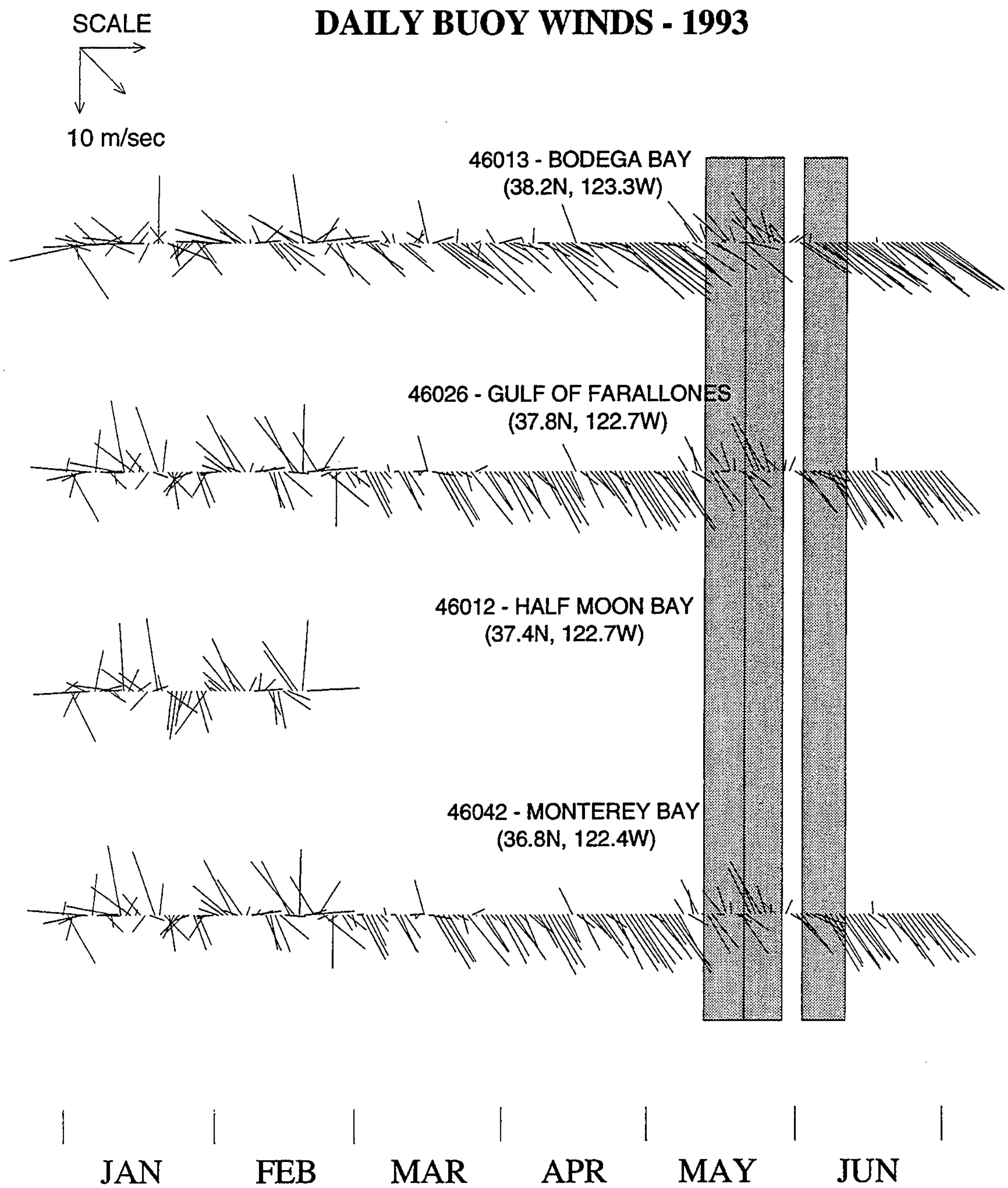
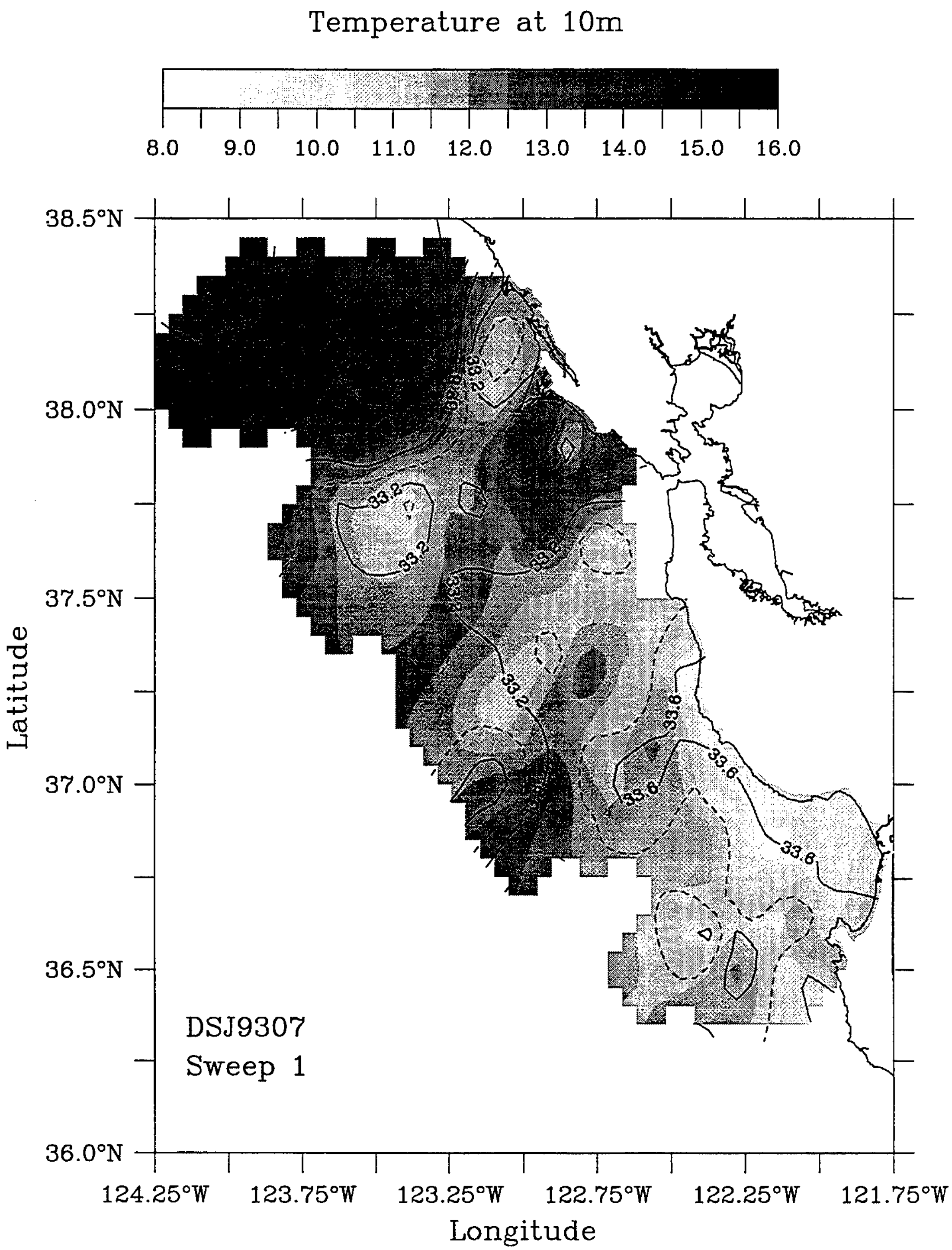

SCALE
DAILY BUOY WINDS - 1993
10 m/sec
46013 - BODEGA BAY
(38.2N, 123.3W)
46026 - GULF OF FARALLONES
(37.8N, 122.7W)
46012 - HALF MOON BAY
(37.4N, 122.7W)
46042 - MONTEREY BAY
(36.8N, 122.4W)
JAN
FEB
MAR
APR
MAY
JUN

Figure 2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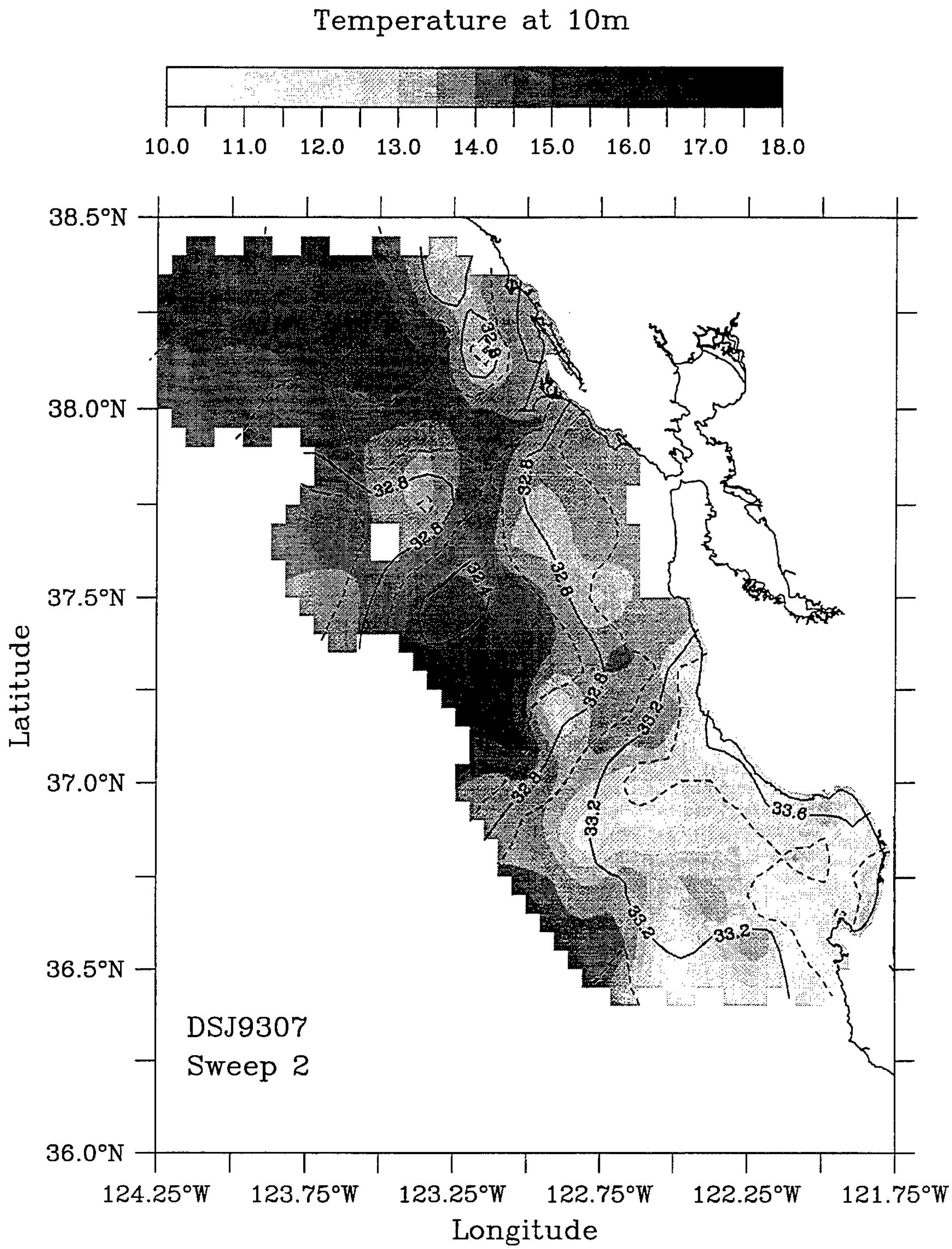
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
16.0
38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
124.25°W
123.75°W
123.25°W
122.75°W
122.25°W
121.75°W
Longitude
33.2
33.6
DSJ9307
Sweep 1

Figure 3



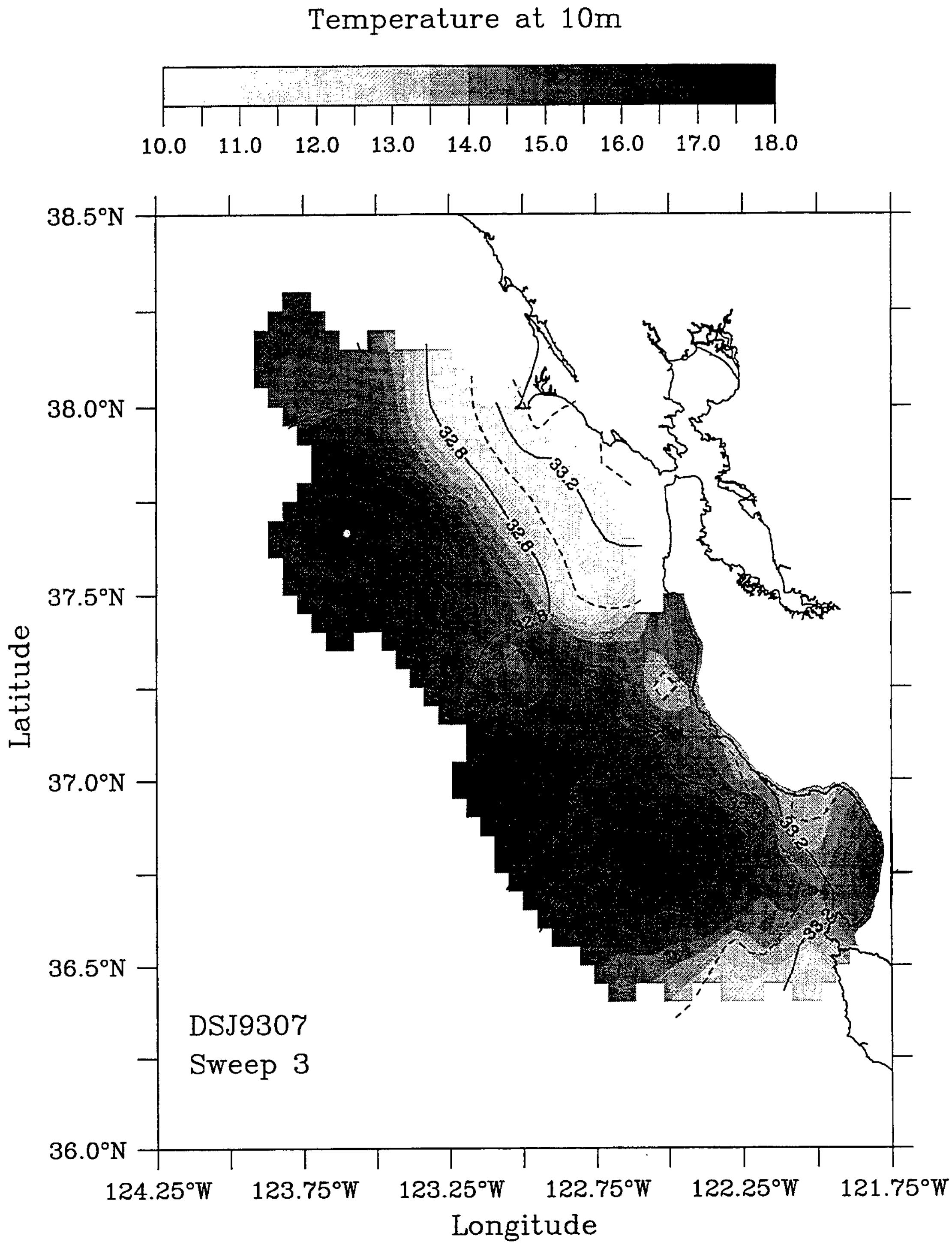
Temperature at 10m
10.0
11.0
12.0
13.0
14.0
15.0
16.0
17.0
18.0
38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
124.25°W
123.75°W
123.25°W
122.75°W
122.25°W
121.75°W
Longitude
DSJ9307
Sweep 2
32.8
33.2
33.6

Figure 4

lower salinity signal.

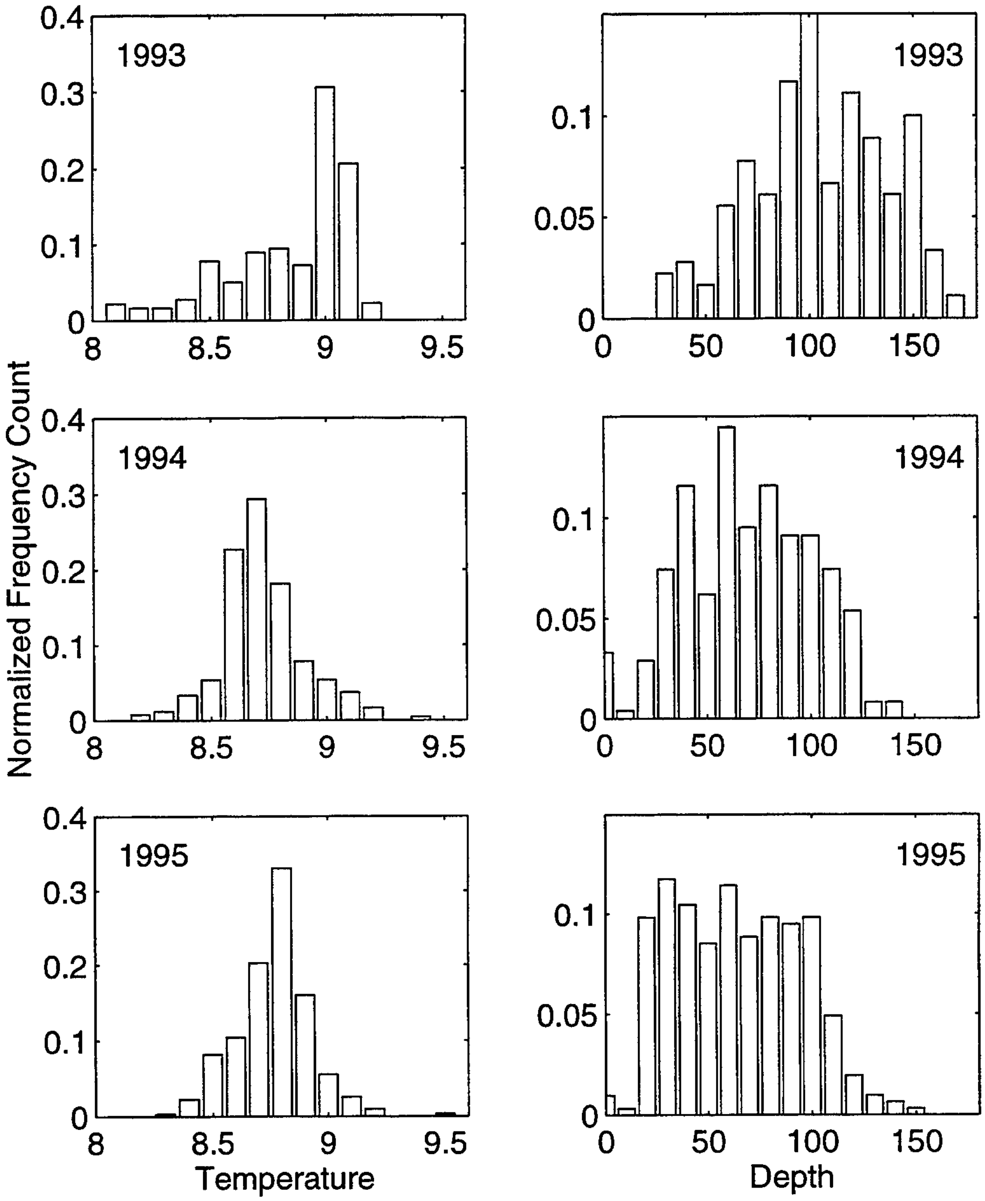
Upwelling-favorable winds returned at the start of Sweep 3 and remained for the duration of the survey (Fig. 2). The oceanic response to the return of upwelling wind conditions was rapid (Fig. 5). A surface front was well-defined, separating cooler, saline inshore water and warmer, fresher offshore water. A large eddy-like feature developed off Monterey Bay, a feature noted by Rosenfeld et al. (1994) after the return of upwelling conditions following a wind relaxation. About 60 km in diameter, it was defined by very warm and relatively fresh water (> 15.0°C, < 32.9) at its center. Along the outer edge of the survey grid, near-surface temperatures were the warmest of all three sweeps. This heating most likely occurred during the relaxation conditions of the previous sweep. Send et al. (1987) suggest that increased surface heating during a relaxation event may be from a combination of solar insolation during light winds and poleward advection of warmer water from the south. In this case, however, onshore advection of frontal water likely caused the increase in temperature along the outer edge of the survey area. Temperatures near the Pt. Año Neuvo upwelling center were still warm (> 11.5°C). Near Pt. Reyes, however, temperatures were cooler, most likely due to advection of cooler, recently-upwelled water from the north in combination with the reestablishment of local upwelling. Also, there is a temporal bias on the spatial sampling of data from this grid. When the ship started this sweep near Cypress Point in the south, upwelling conditions had just begun. Upwelling-favorable winds had been blowing for a week when the ship sampled the northern region off Pt. Reyes, producing a non-synoptic bias in the results. Data from the northern part of the grid, then, are representative of a longer period of upwelling rather than representing simply a latitudinal change in ocean structure.

Analysis of temperature and depth variations of the 26.2 potential density (σ_θ) surface is described here to provide insight into the mixing and spatial structure of local water types and the temporal variations in these structures. The 26.2 isopycnal had an average depth close to 100 m, and ranged between 40 m and 150 m for all three upwelling seasons surveyed (Fig. 6). The range of depths within an upwelling season varied between years. Consistently found below the mixed layer in this survey,



Temperature at 10m
10.0
11.0
12.0
13.0
14.0
15.0
16.0
17.0
18.0
38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
32.8
33.2
DSJ9307
Sweep 3
124.25°W
123.75°W
123.25°W
122.75°W
122.25°W
121.75°W
Longitude

Figure 5



Normalized Frequency Count
1993
1994
1995
Temperature
Depth
0
0.1
0.2
0.3
0.4
0.05
8
8.5
9
9.5
50
100
150

Figure 6

the 26.2 surface represents the upper ocean density structure.

During Sweep 1 of the 9307 survey, the 26.2 surface deepened from 50 m onshelf to 140 m offshelf (Fig. 7). The upward slope of this surface along the entire coast may represent a dynamic adjustment to the equatorward California Current, and is also characteristic of a mature upwelling state, consistent with temperature and salinity observations. The slope was steepest northwest of Pt. Reyes, corresponding to the area of steepest temperature and salinity gradients. The warmest water on this surface, > 9.0°C, was found south of 37.0°N.

The large meander or eddy feature seen in the near-surface temperature and salinity fields in Sweep 2 corresponded to a local deepening of the 26.2 isopycnal, as well as a decrease in the temperature on this surface (Fig. 8). As with the first sweep, water warmer than 9.0°C was restricted to the southern region of the sampling area. The increased depth of this surface in the southern portion of the survey grid is most likely a vertical displacement caused by the onshore, horizontal advection of the warmer, fresher meander seen in the current and salinity fields (Fig. 4).

The 26.2 isopycnal deepened by the time Sweep 3 was conducted (Fig. 9), the greatest depths (> 140 m) were offshore of Monterey Bay and Pt. Reyes. Off Monterey Bay, the local deepening corresponded to the warm and fresh eddy-like feature seen in the temperature and salinity fields. Water warmer than 9.0°C was again found south of 37.0°N, and also offshore of the Gulf of the Farallones (37.7°N 123.6°W). Throughout the area, temperatures on the 26.2 surface showed a general warming trend as the season progressed.

Despite poleward and onshore winds during Sweep 1, flow off Pt. Reyes was equatorward and offshore (Fig. 10). Strong velocities (> 50 cm/s) coincided with steep horizontal temperature and salinity gradients. This filament appears to be the nearshore portion of an anticyclonic eddy or meander that extended beyond the range of the survey, suggested by the associated onshore velocities north of 38.0°N. This flow feature was persistent to 100 m depth, as were its temperature and salinity signals. While it varied in location and extent with time, this filament appears to be a permanent or recurring feature in this region, and will be referred to as the Pt. Reyes

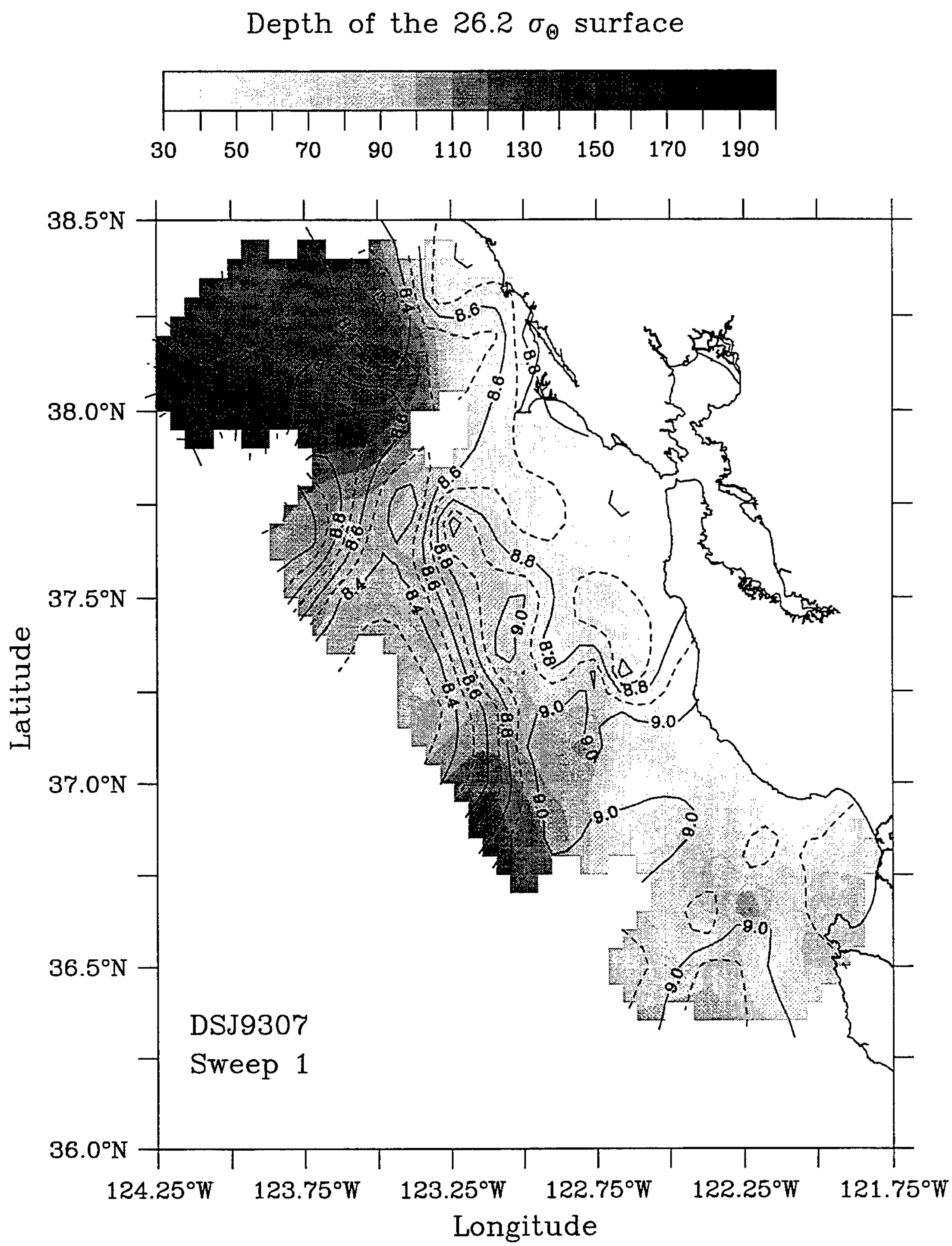
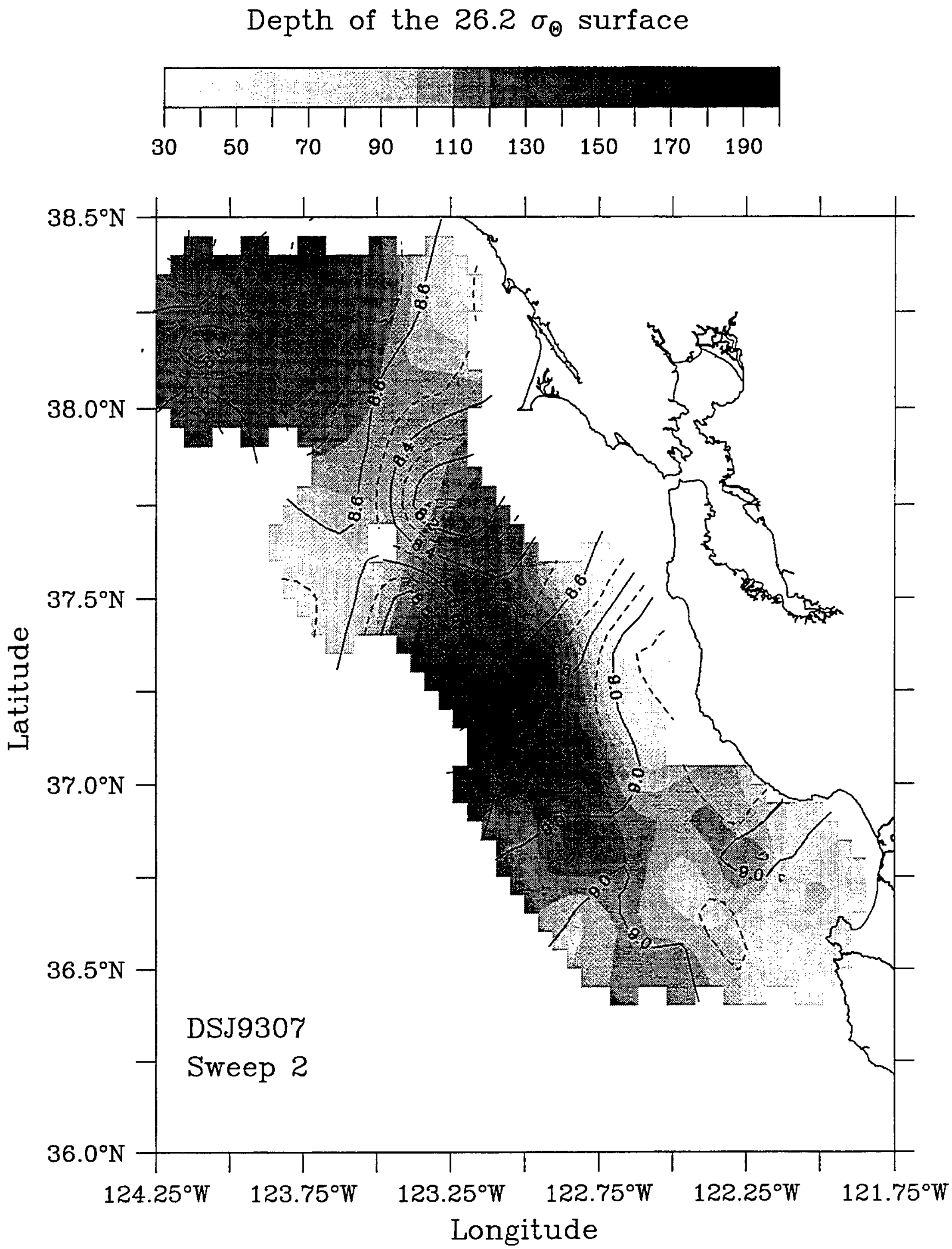
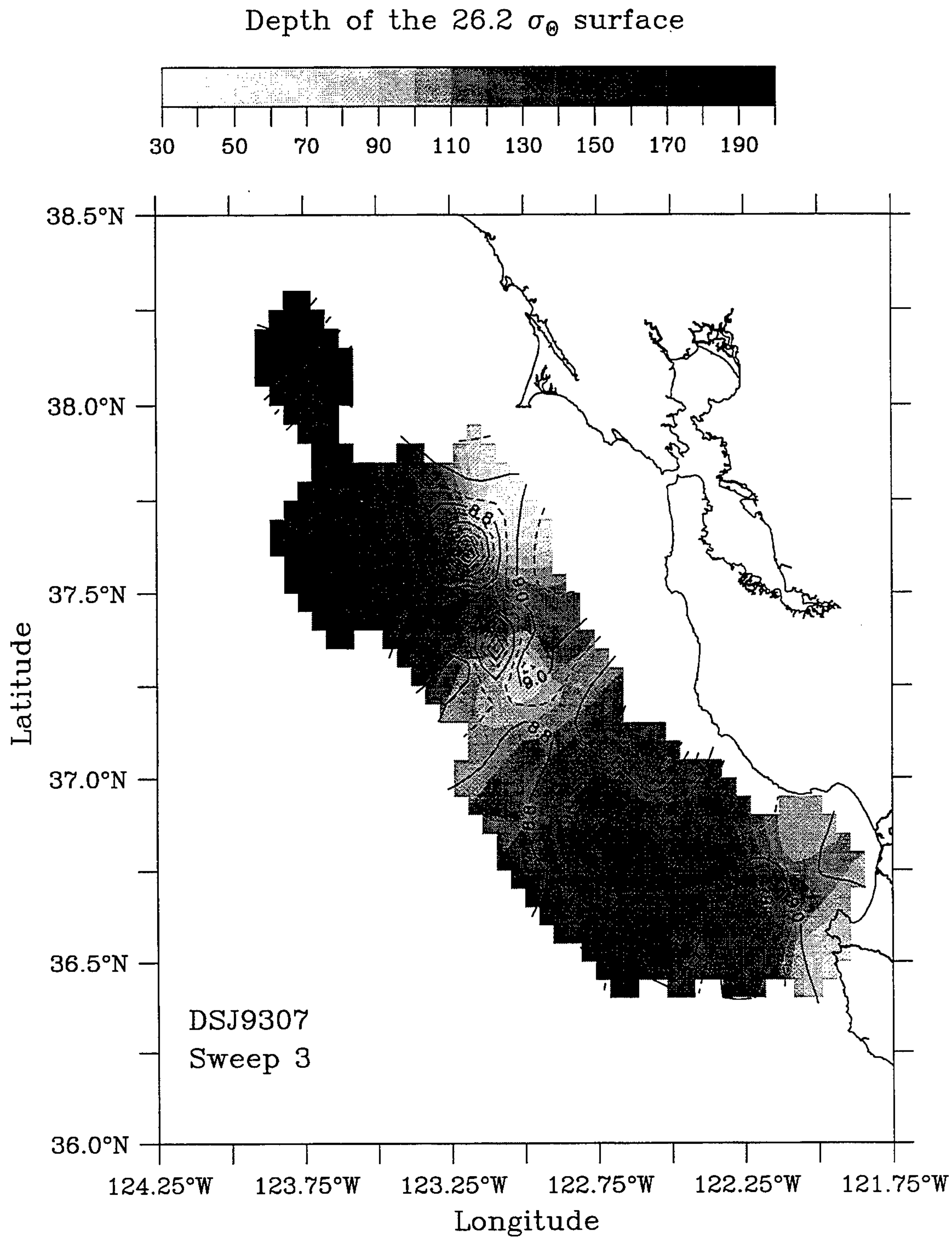

Depth of the 26.2 σ_Θ surface
30 50 70 90 110 130 150 170 190
38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
124.25°W 123.75°W 123.25°W 122.75°W 122.25°W 121.75°W
Longitude
DSJ9307
Sweep 1

Figure 7



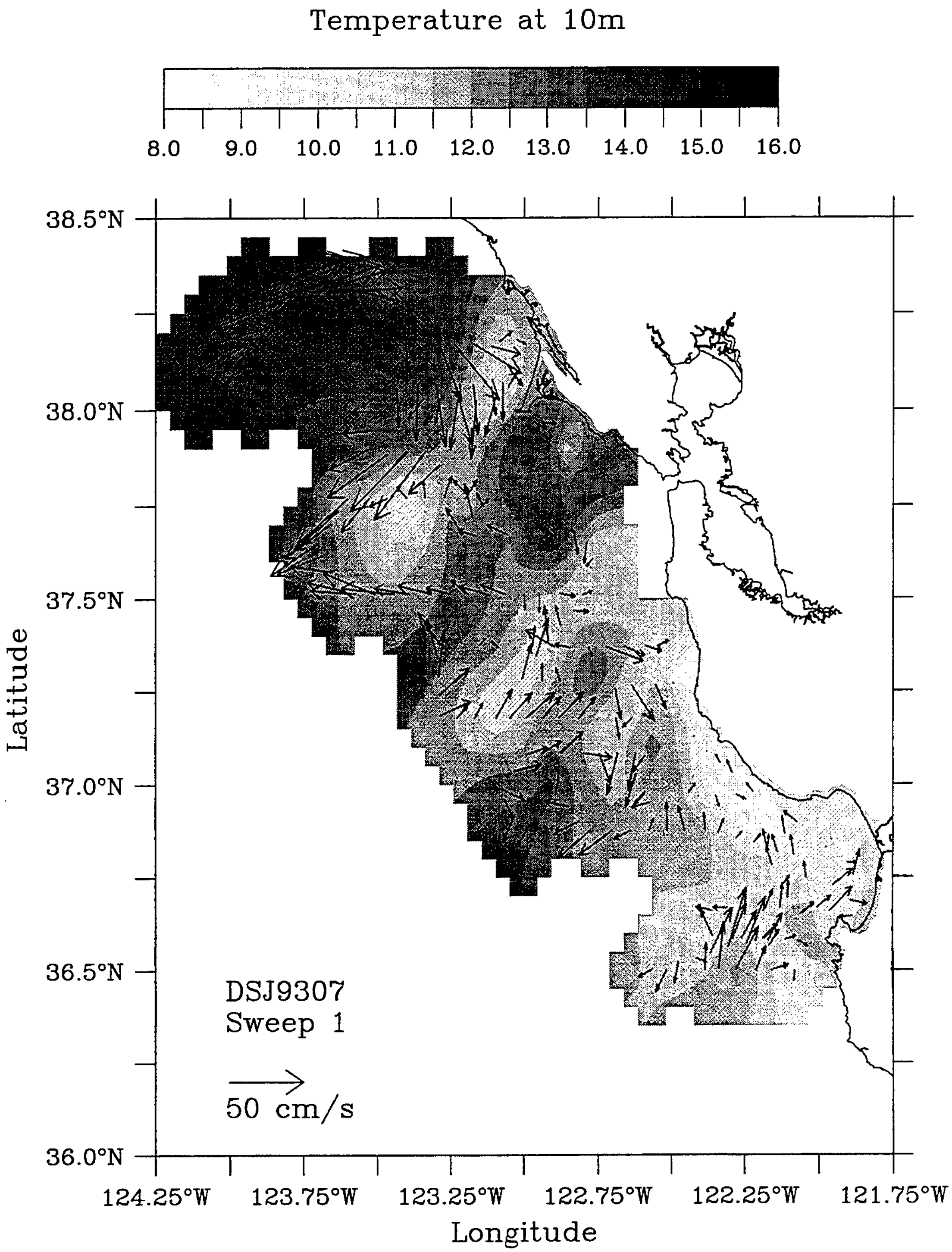
Depth of the 26.2 σ_Θ surface
30
50
70
90
110
130
150
170
190
38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
124.25°W
123.75°W
123.25°W
122.75°W
122.25°W
121.75°W
Longitude
DSJ9307
Sweep 2

Figure 8



Depth of the 26.2 σ_Θ surface
30
50
70
90
110
130
150
170
190
38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
124.25°W
123.75°W
123.25°W
122.75°W
122.25°W
121.75°W
Longitude
DSJ9307
Sweep 3

Figure 9



Temperature at 10m
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
16.0
38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
124.25°W
123.75°W
123.25°W
122.75°W
122.25°W
121.75°W
Longitude
DSJ9307
Sweep 1
50 cm/s

Figure 10

filament. Poleward and onshore currents near Monterey Bay during this sweep may be forced by local winds.

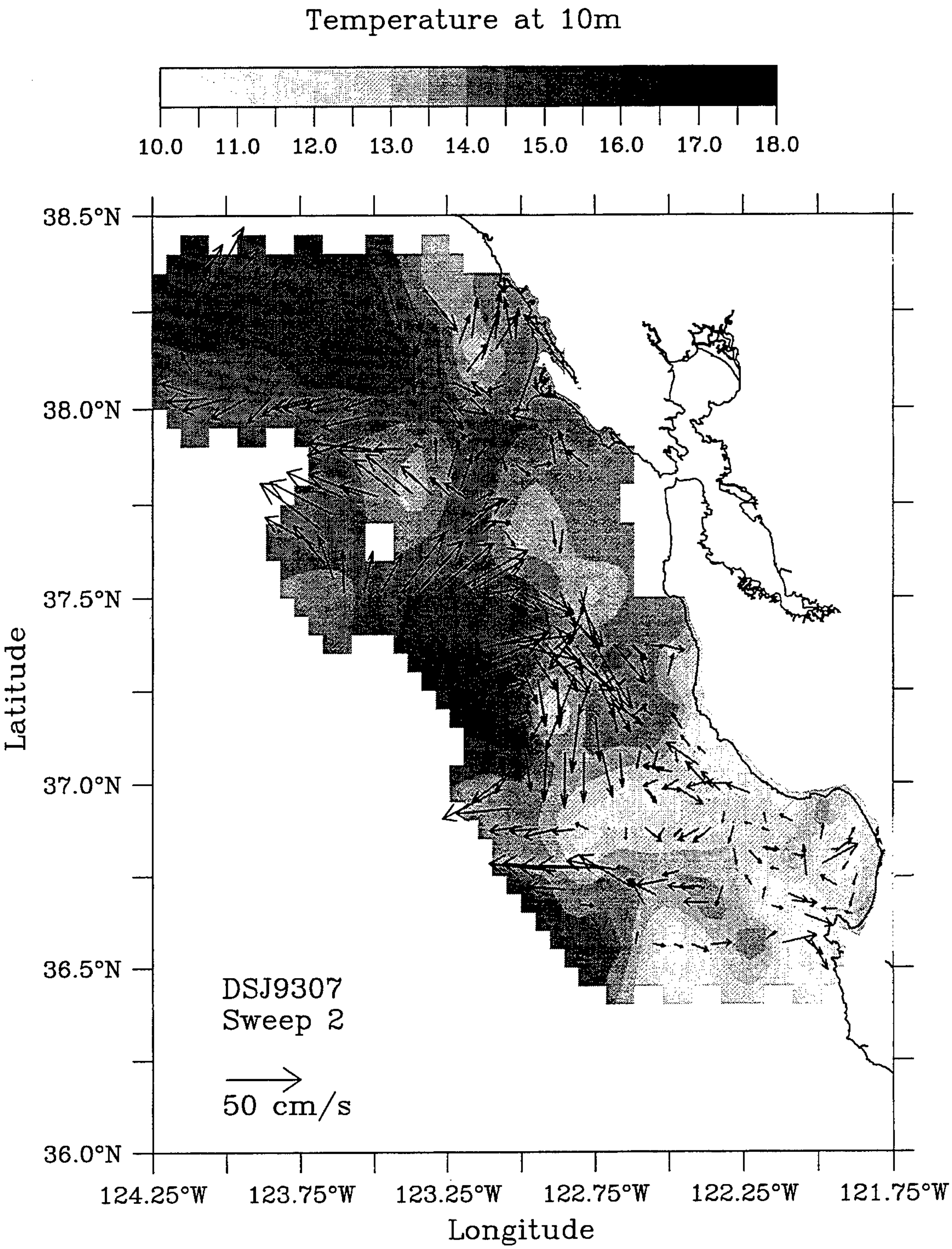
During Sweep 2 of DSJ9307, local winds continued to blow from the southeast and the Pt. Reyes filament north of 38.25°N persisted in its equatorward and offshore path (Fig. 11). Evidence of this filament as part of an anticyclonic eddy is seen in the poleward flow west of 123.75°W. Strong anticyclonic flow (> 50 cm/s) off Half Moon Bay defined a warm, fresh meander or eddy. These currents do not support the idea that warm, fresh water is advected from the south during wind relaxations/reversals, as Send et al. (1987) found near Pt. Reyes. Instead, warm, fresh water appears to have been advected onshore in this case.

The near-surface currents were mainly to the south and seaward during Sweep 3 (Fig. 12). The offshore component of the Pt. Reyes filament, generally observed shearing offshore parallel to the Point, was displaced approximately 75 km south. The large anticyclonic eddy found off Monterey Bay corresponded to a warm, fresh water type in the hydrographic data (Fig. 5). A similar circulation feature has been observed previously in this area during an upwelling event (Rosenfeld et al., 1994).

B. SPRING-SUMMER 1994

The 1994 spring-summer was more typical of the upwelling season off central California than was 1993. Winds were predominantly from the northwest along the central California coast, punctuated by brief relaxation or reversal events throughout the survey (Fig. 13). The May and June *El Niño Watch Advisory* (issues 94-05, 94-06, CoastWatch, SWFSC, La Jolla, CA) showed that the signal from the previous tropical ENSO event was barely detectable in the spring-summer SST record off central California.

As expected for persistent northwesterly winds, the near-surface temperature and salinity fields during Sweep 1 represented a mature upwelling state along central California (Fig. 14). Cooler and more saline recently-upwelled water was found along the shore, closest to coastal points, and was separated from warmer and fresher



Temperature at 10m
10.0
11.0
12.0
13.0
14.0
15.0
16.0
17.0
18.0
38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
DSJ9307
Sweep 2
50 cm/s
124.25°W
123.75°W
123.25°W
122.75°W
122.25°W
121.75°W
Longitude

Figure 11

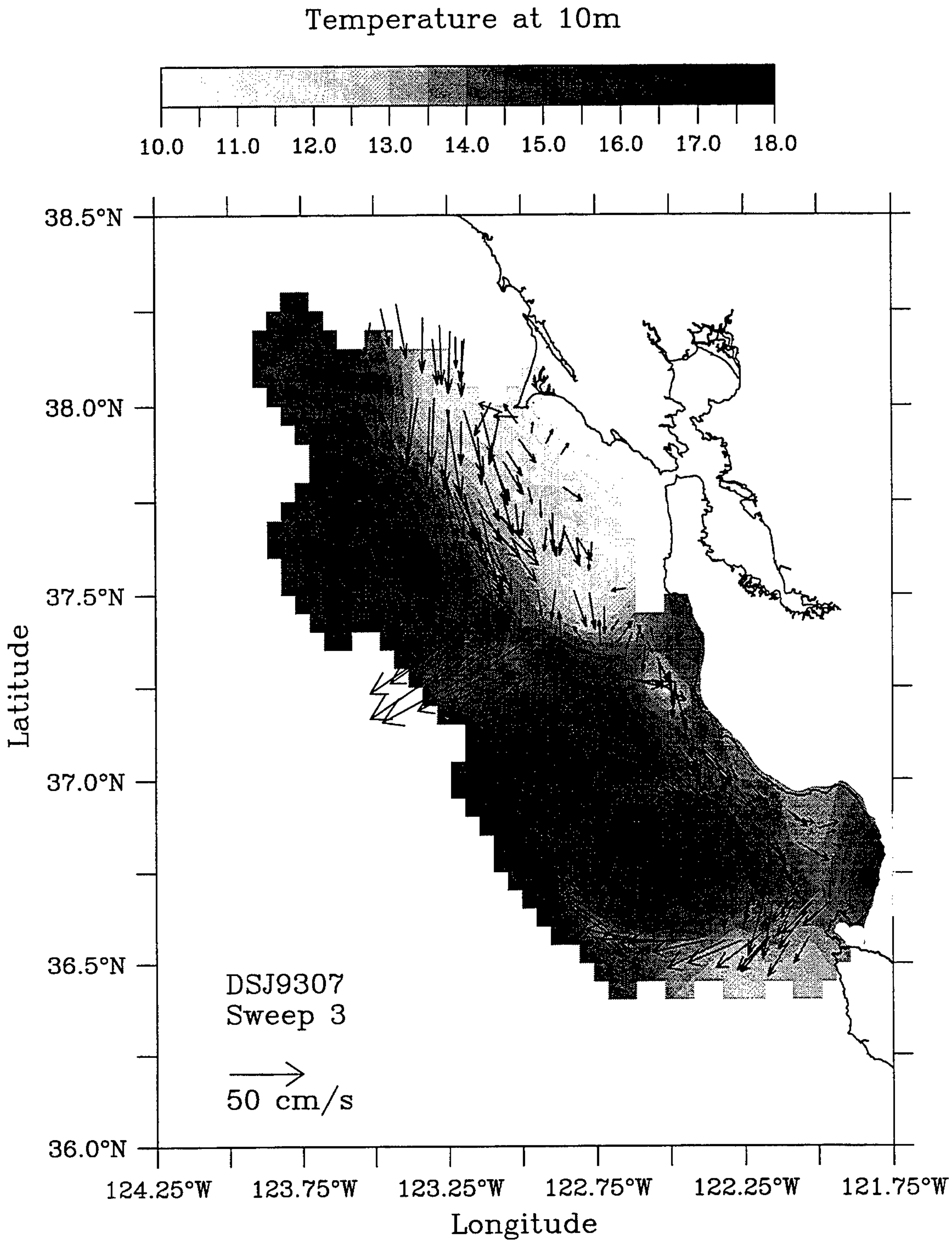

Temperature at 10m
10.0
11.0
12.0
13.0
14.0
15.0
16.0
17.0
18.0
38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
DSJ9307
Sweep 3
50 cm/s
124.25°W
123.75°W
123.25°W
122.75°W
122.25°W
121.75°W
Longitude

Figure 12

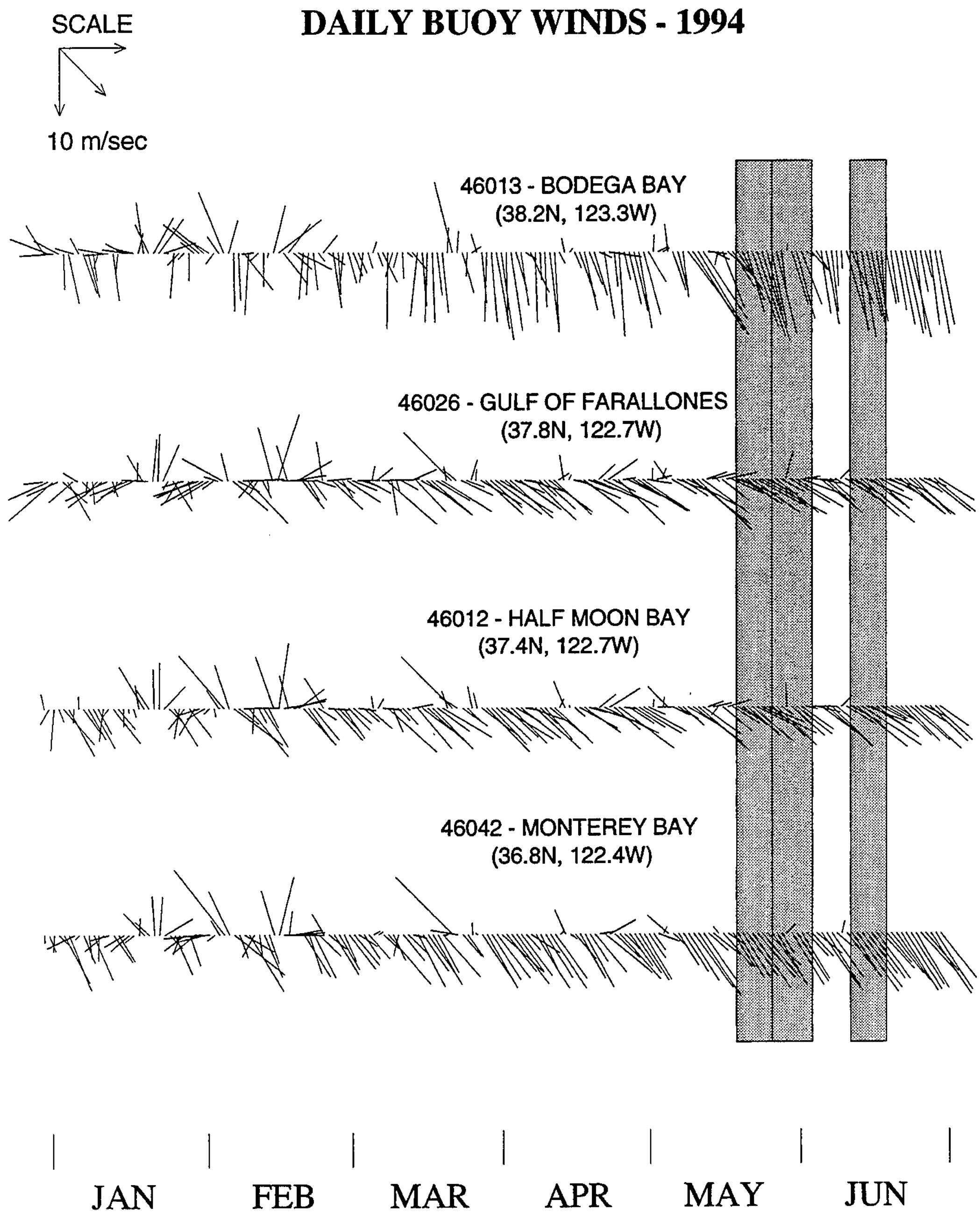

DAILY BUOY WINDS - 1994
SCALE
10 m/sec
46013 - BODEGA BAY
(38.2N, 123.3W)
46026 - GULF OF FARALLONES
(37.8N, 122.7W)
46012 - HALF MOON BAY
(37.4N, 122.7W)
46042 - MONTEREY BAY
(36.8N, 122.4W)
JAN
FEB
MAR
APR
MAY
JUN

Figure 13

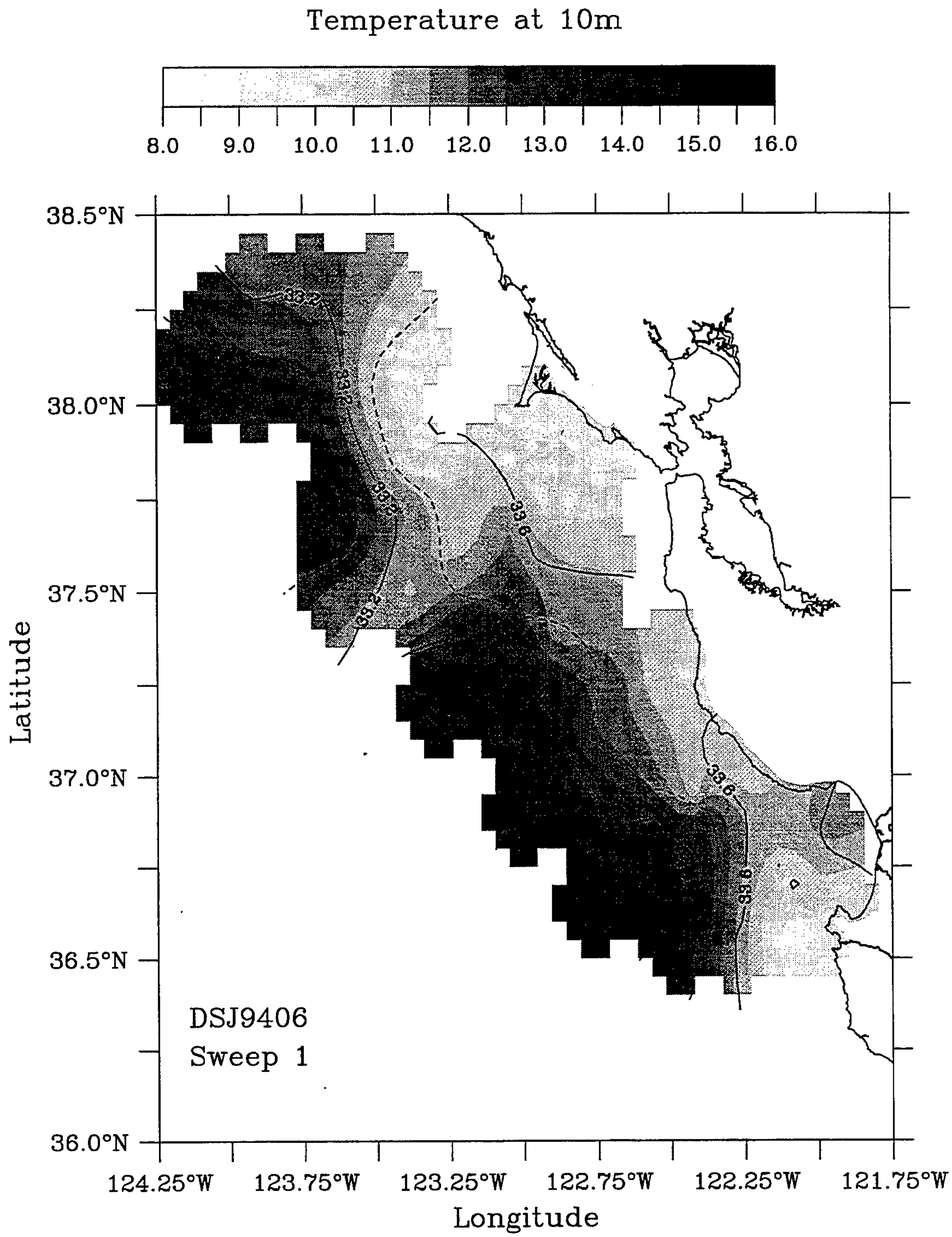

Temperature at 10m
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
16.0
38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
124.25°W
123.75°W
123.25°W
122.75°W
122.25°W
121.75°W
Longitude
33.2
33.6
DSJ9406
Sweep 1

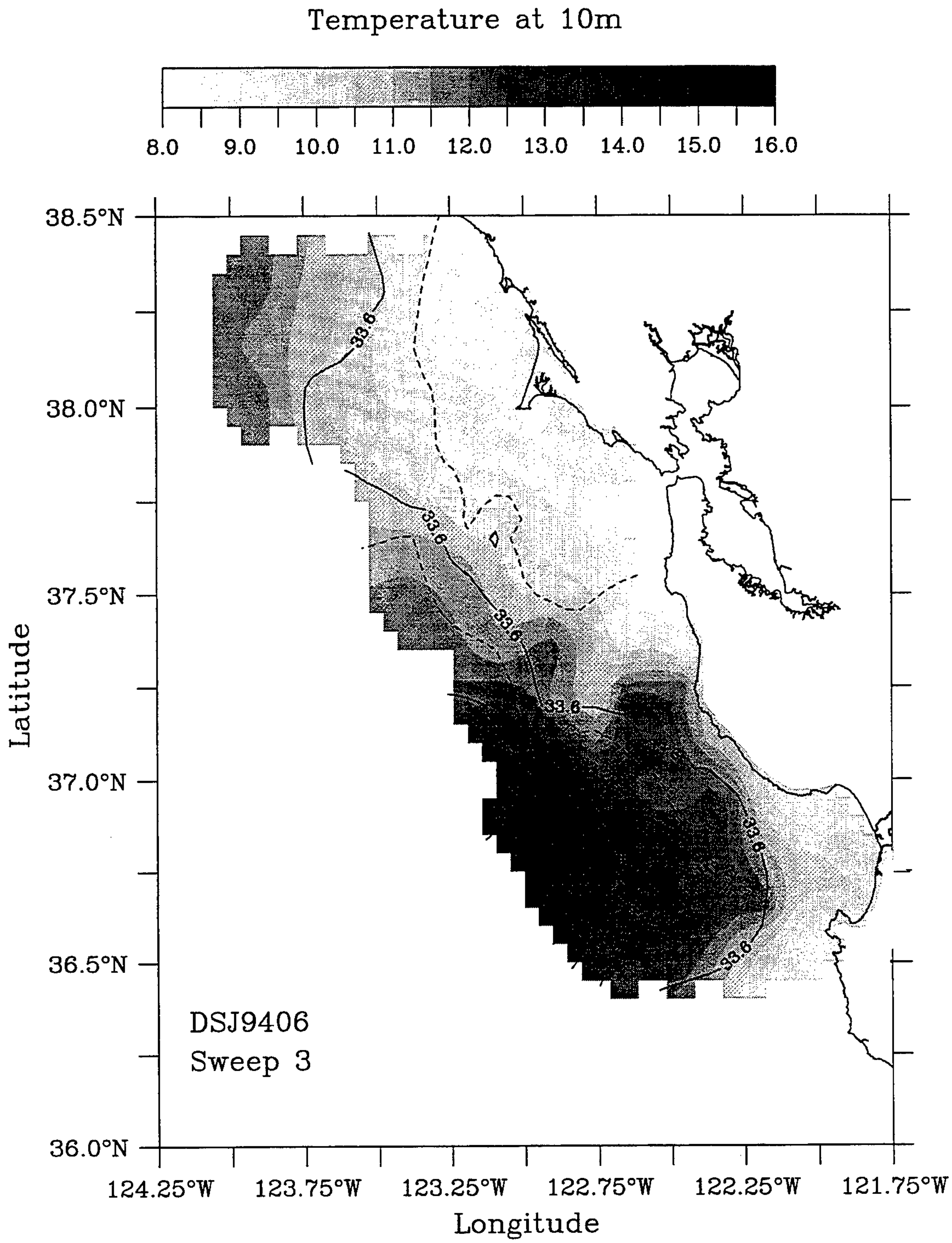
Figure 14

offshore water by temperature and salinity fronts. Without the influence of the ENSO signal, or poleward wind stress, the temperature range was noticeably lower than in 1993, 10.0°-13.8°C. The Pt. Reyes filament was, as in 1993, a region of steep temperature and salinity gradients that extended to the south and then seaward.

Upwelling-favorable winds also persisted through Sweeps 2 and 3 (Fig. 13). Overall, the CTD observations for Sweeps 2 and 3 resembled those of Sweep 1, with the presence of colder, saline water extending equatorward and offshore from upwelling centers. Over the course of the survey, a large (60 km diameter) warm, fresh eddy developed off Monterey Bay (> 12.8°C, < 33.2), evident in the Sweep 3 CTD data (Fig. 15), concurrent with the return of upwelling after a wind relaxation event.

During the 1994 survey, the 26.2 isopycnal depth ranged from 30 m onshelf to 120 m offshelf (Fig. 6). During Sweep 1 the coolest temperatures on this surface were north of 38.0°N (Fig. 16), presumably due to an increased contribution of Pacific Subarctic Water in this region. The 26.2 isopycnal shoaled significantly throughout the survey area while maintaining its alongshore alignment. Unlike the 1993 upwelling season, when the warmest water was confined in the southern survey area, the warmest portion of this surface throughout the 1994 survey was in the Gulf of the Farallones. Off Monterey Bay, the 26.2 surface deepened by the third sweep, coincident with the warm, fresh eddy seen in the hydrography (Fig. 15). Most likely, the water in this eddy moved onshore in an adjustment to the relaxation of upwelling winds, and depressed local density surfaces. This vertical displacement appears to be similar to the displacement by onshore advection of warmer, fresher water in the second sweep of 1993 off Monterey Bay, despite the fact that temperatures were cooler on this surface in 1994.

The coastal circulation off central California was very complex during the 1994 spring-summer surveys. In addition to offshore Ekman transport and equatorward movement of near-surface waters typically found during mature upwelling conditions, some poleward and onshore currents were observed along the offshore edge of the



Temperature at 10m
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
16.0
38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
33.6
DSJ9406
Sweep 3
124.25°W
123.75°W
123.25°W
122.75°W
122.25°W
121.75°W
Longitude

Figure 15

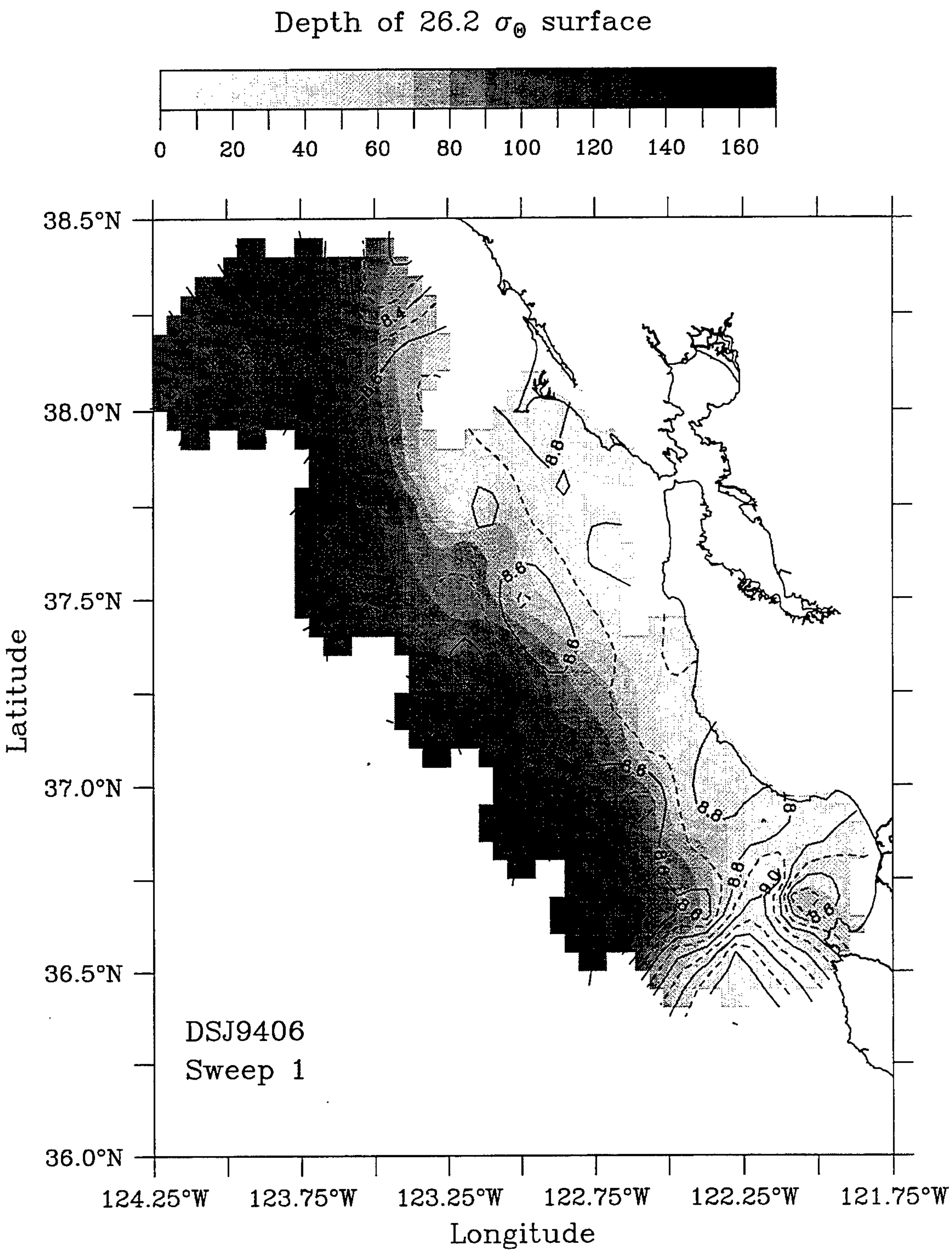

Depth of 26.2 σ_Θ surface
0
20
40
60
80
100
120
140
160
38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
124.25°W
123.75°W
123.25°W
122.75°W
122.25°W
121.75°W
Longitude
DSJ9406
Sweep 1

Figure 16

sampling area. Water moving poleward in this frontal zone was warmer than the adjacent cold upwelled water. The poleward currents were generally found just offshore and south of these upwelled filaments. This circulation pattern implies a return flow of less dense water away from the eastern edge of the California Current in response to the intrusion of rapid currents of dense upwelled water.

A striking example of poleward flow during upwelling-favorable conditions was found in Sweep 2 (Fig. 17). Despite fairly continuous equatorward wind stress, strong poleward currents (about 50 cm/s) over the continental slope dominated the southwestern portion of the survey area. This northward flow was vertically coherent to 200 m. Satellite images of SST from Sweeps 1 (Fig. 18) and 2 (Fig. 19) reveal a warm feature in this area that may have advected poleward over time.

During the 1994 upwelling season, persistent or recurring circulation features had characteristic signals in the temperature and salinity fields. The Pt. Reyes filament during the first and last sweeps had equatorward velocities of 20-40 cm/s, veering offshore near 37.60°N (Fig. 20). This filament was less discernable in Sweep 2, although anticyclonic flow in that region coincided with the warm, fresh water seen seaward of the filament (Fig. 17), and may belie the Point Reyes filament as being the result of a onshore advection of an oceanic mesoscale eddy. In Sweep 3, the warm feature off Monterey Bay had strong velocities (25-50 cm/s) and an anticyclonic circulation (Fig. 20).

C. SPRING-SUMMER 1995

Meteorological forcing in the spring-summer season of 1995 was quite similar to that of 1994. The local wind field off central California during this survey was again dominated by northwesterly winds, with episodic relaxation and reversal events (Fig. 21). The slightly positive SST anomalies (< 1.0°C) were considered the result of local oceanographic and meteorological conditions as opposed to equatorial ENSO forcing in the May and June *El Niño Watch Advisory* (issues 95-05, 95-06, CoastWatch, SWFSC, La Jolla, CA). Due to heavy winter storms and an increased

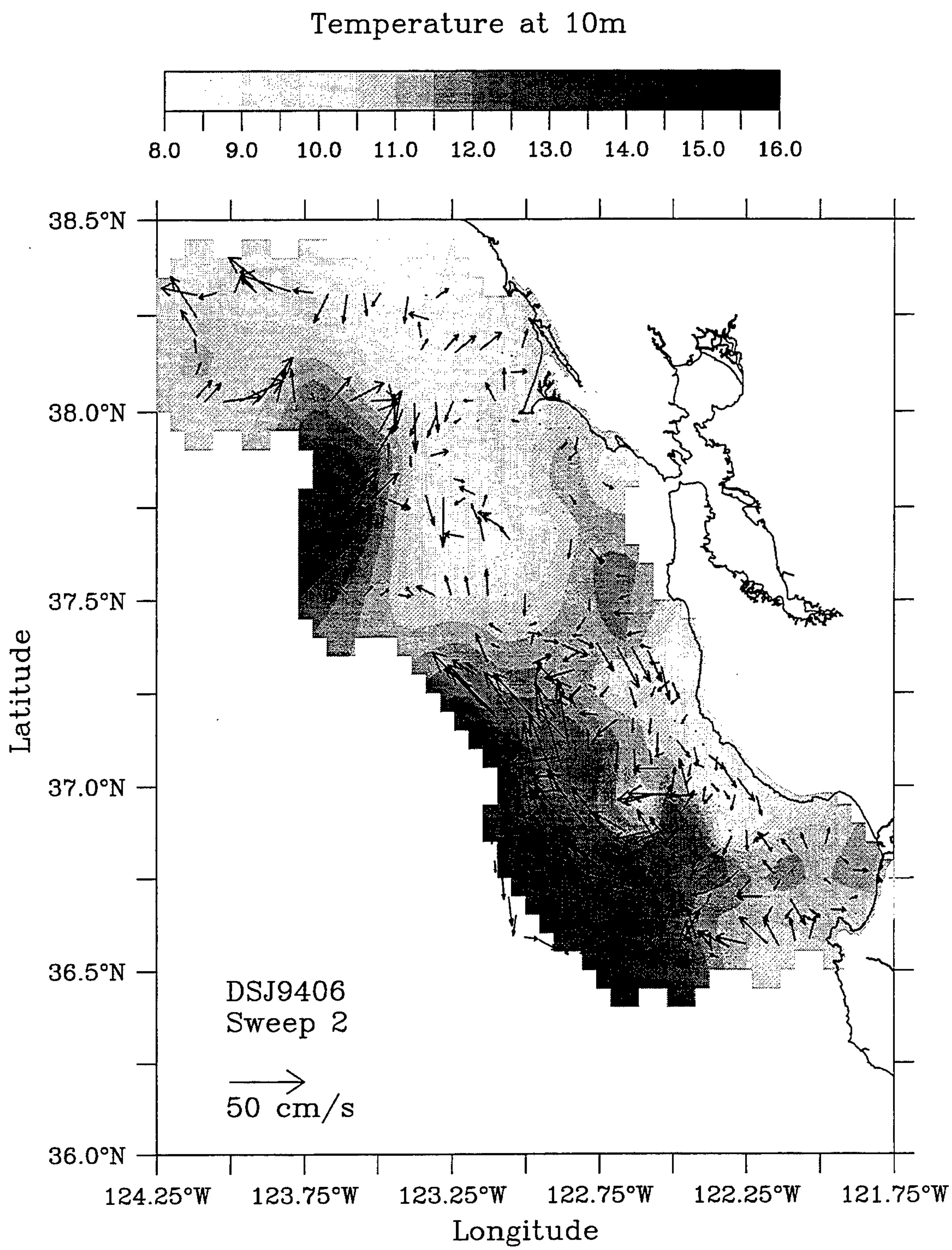
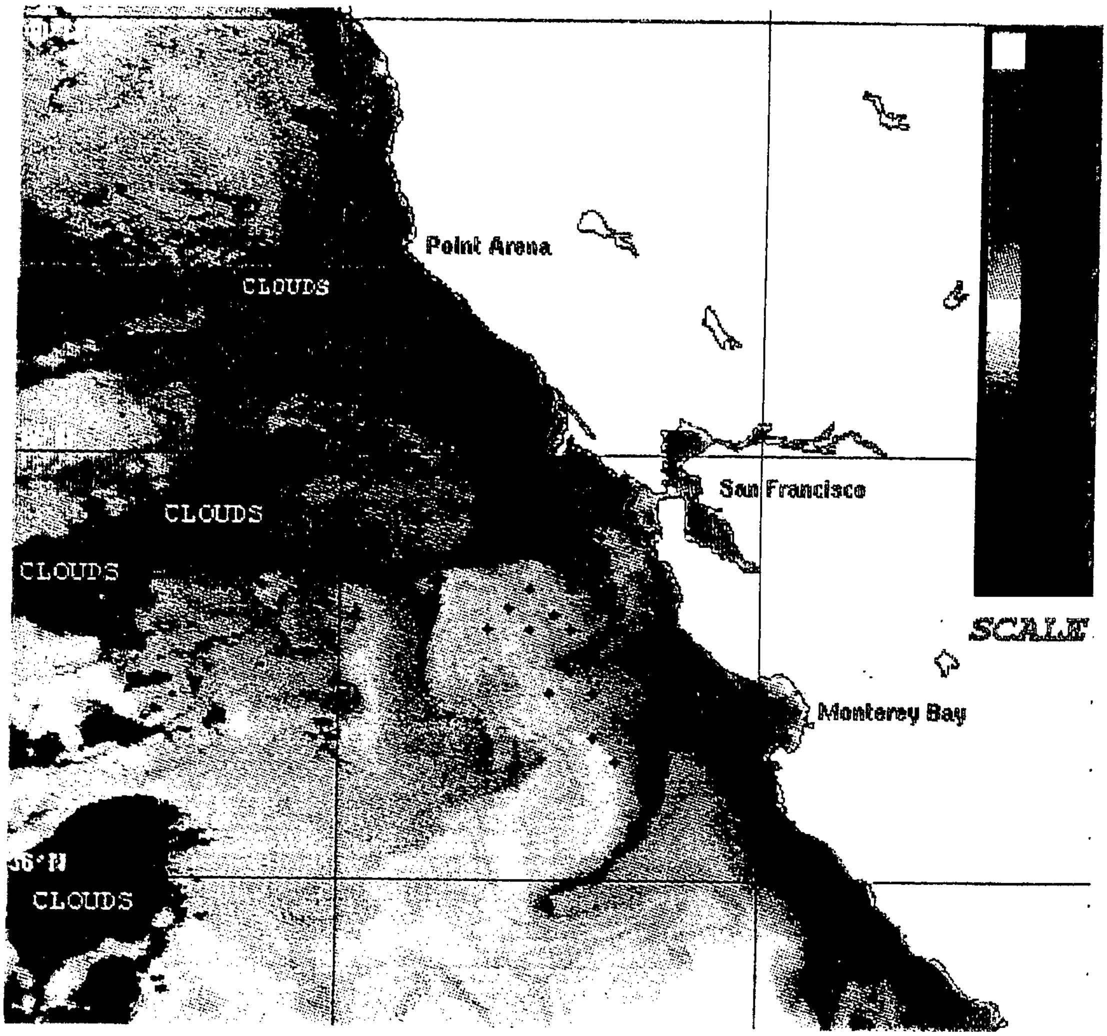

Temperature at 10m
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
16.0
38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
124.25°W
123.75°W
123.25°W
122.75°W
122.25°W
121.75°W
Longitude
DSJ9406
Sweep 2
50 cm/s

Figure 17



Point Arena
CLOUDS
CLOUDS
CLOUDS
San Francisco
SCALE
Monterey Bay
36°N
CLOUDS

Figure 18

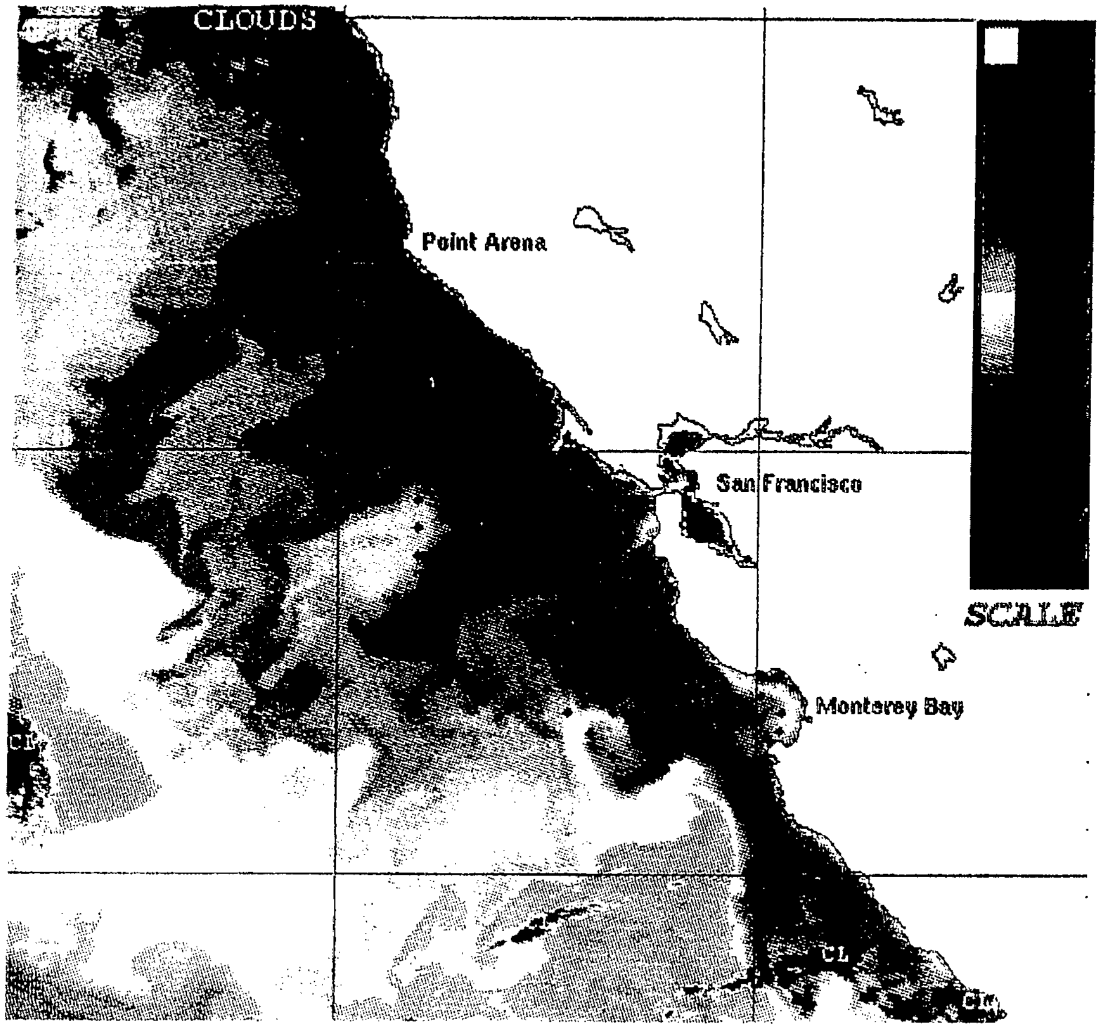


Figure 19

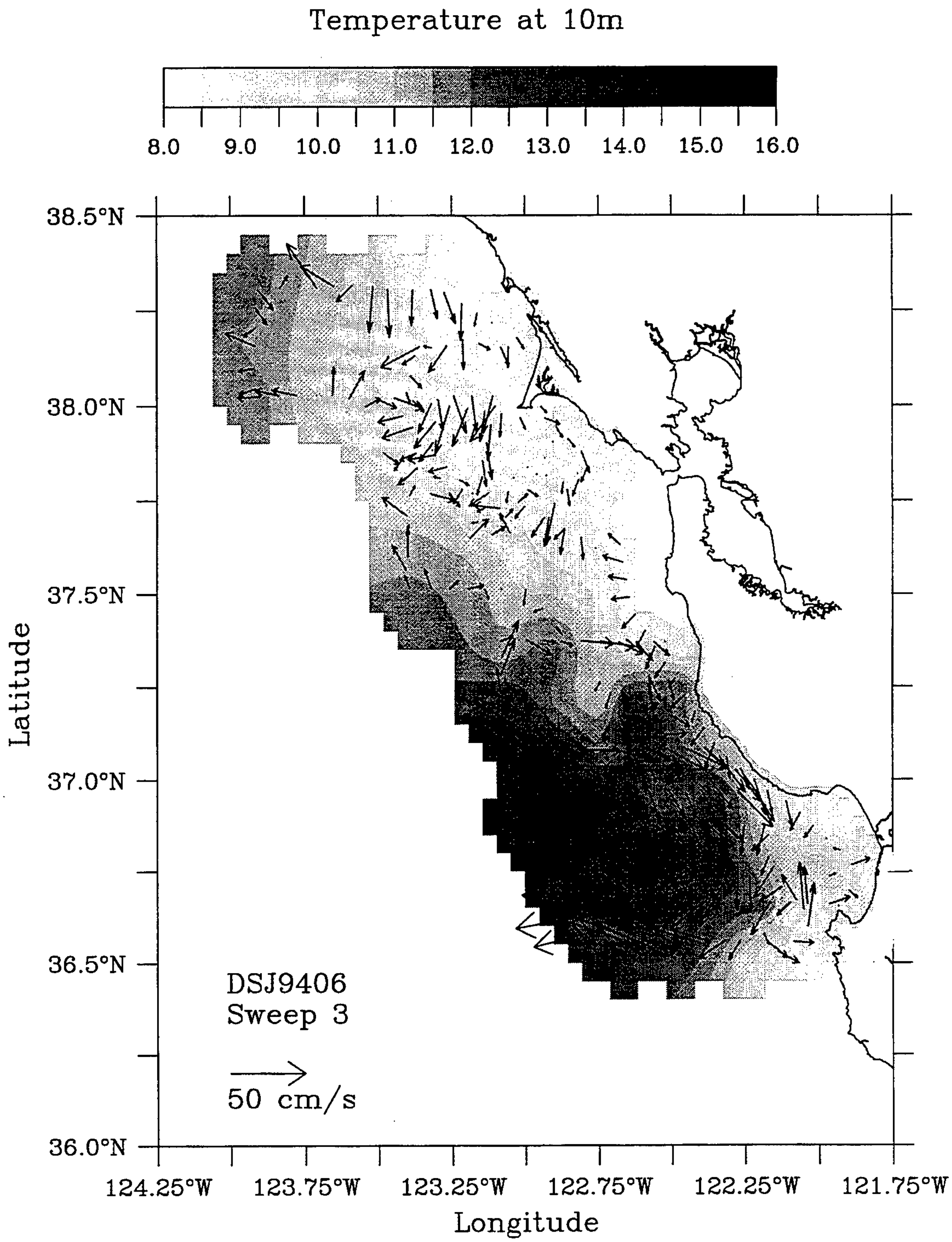

Temperature at 10m
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
16.0
38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
DSJ9406
Sweep 3
50 cm/s
124.25°W
123.75°W
123.25°W
122.75°W
122.25°W
121.75°W
Longitude

Figure 20

DAILY BUOY WINDS - 1995

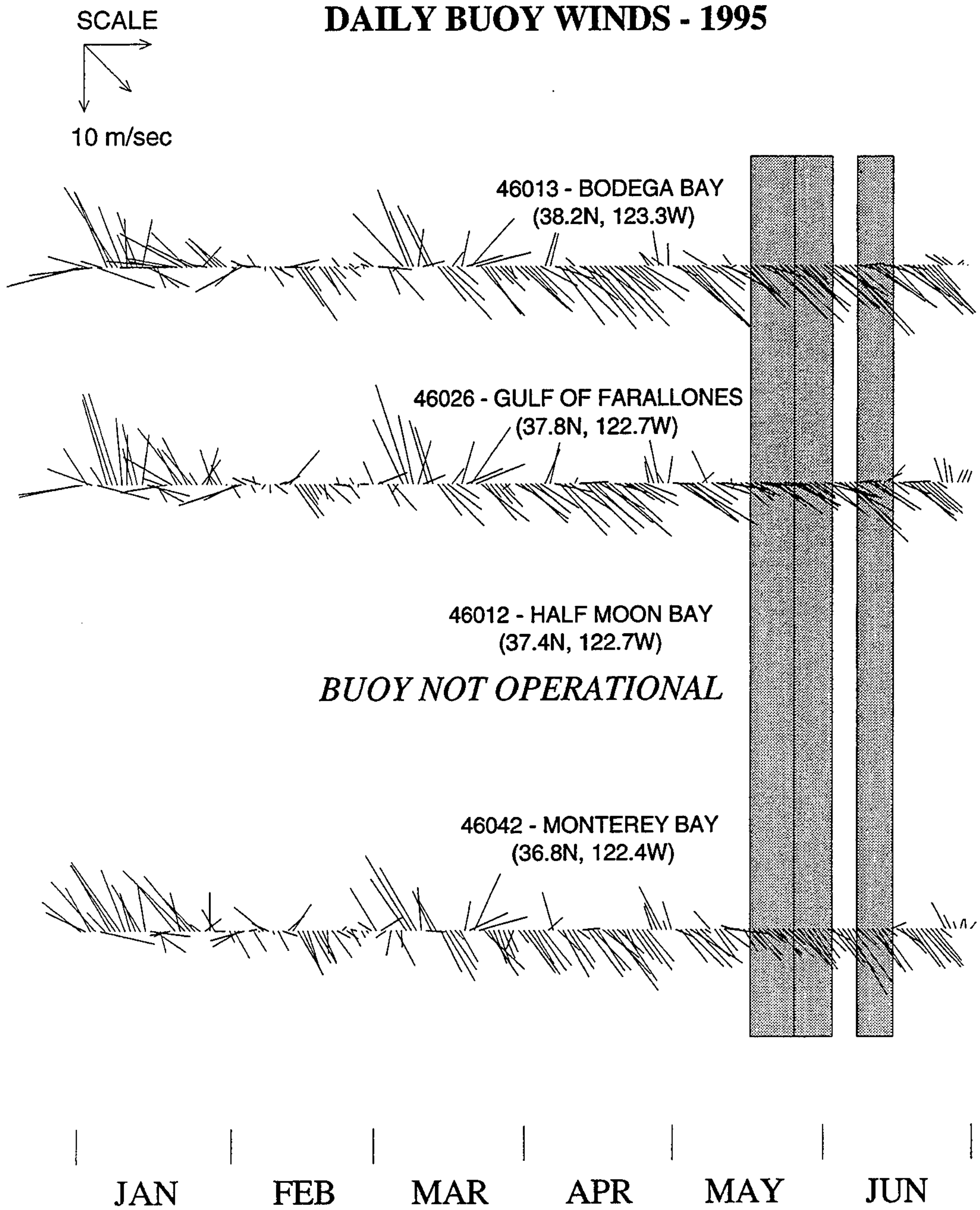
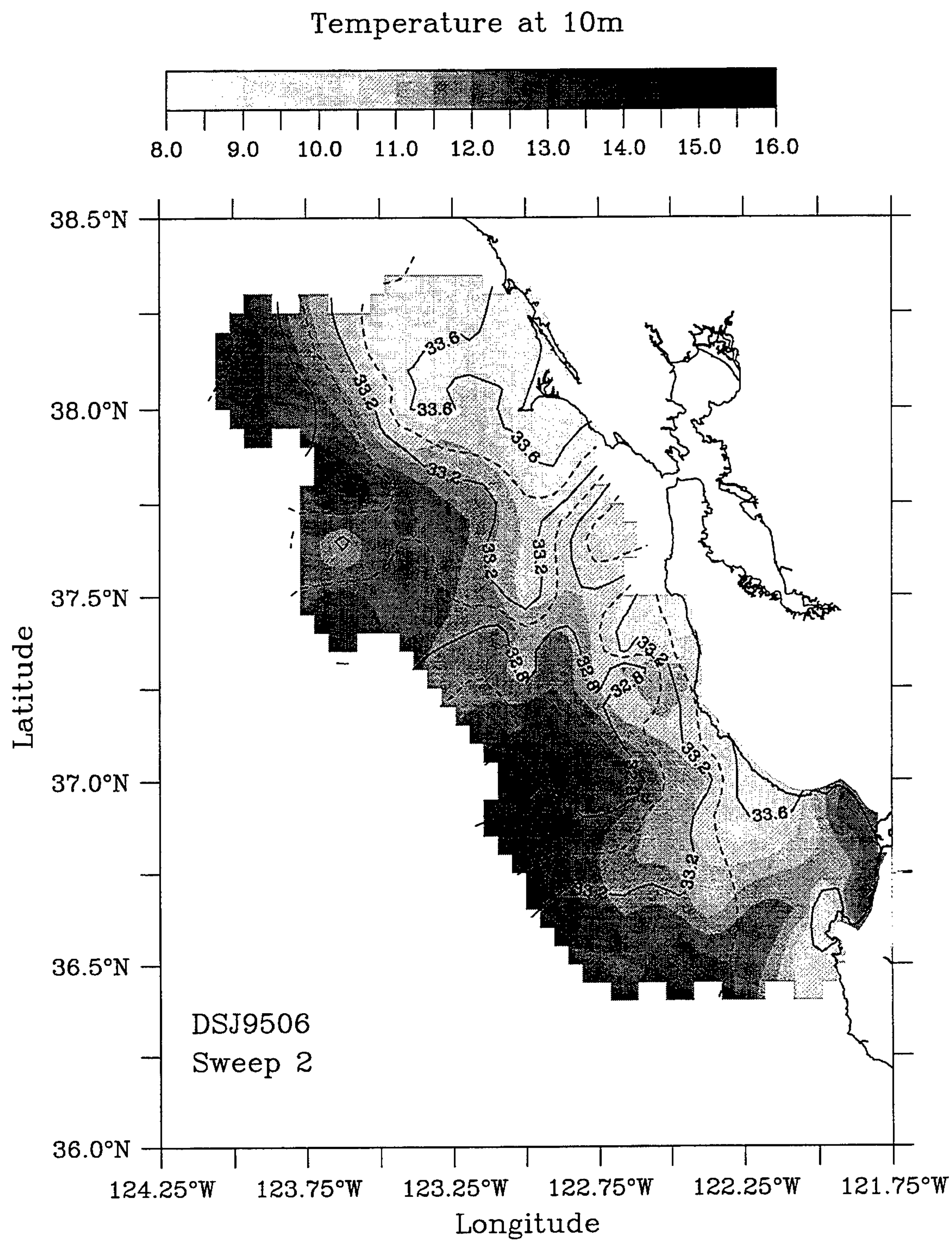


Figure 21

amount of spring rainfall, anomalous quantities of fresh water discharged from San Francisco Bay, notably reducing the regional near-surface salinity signal.

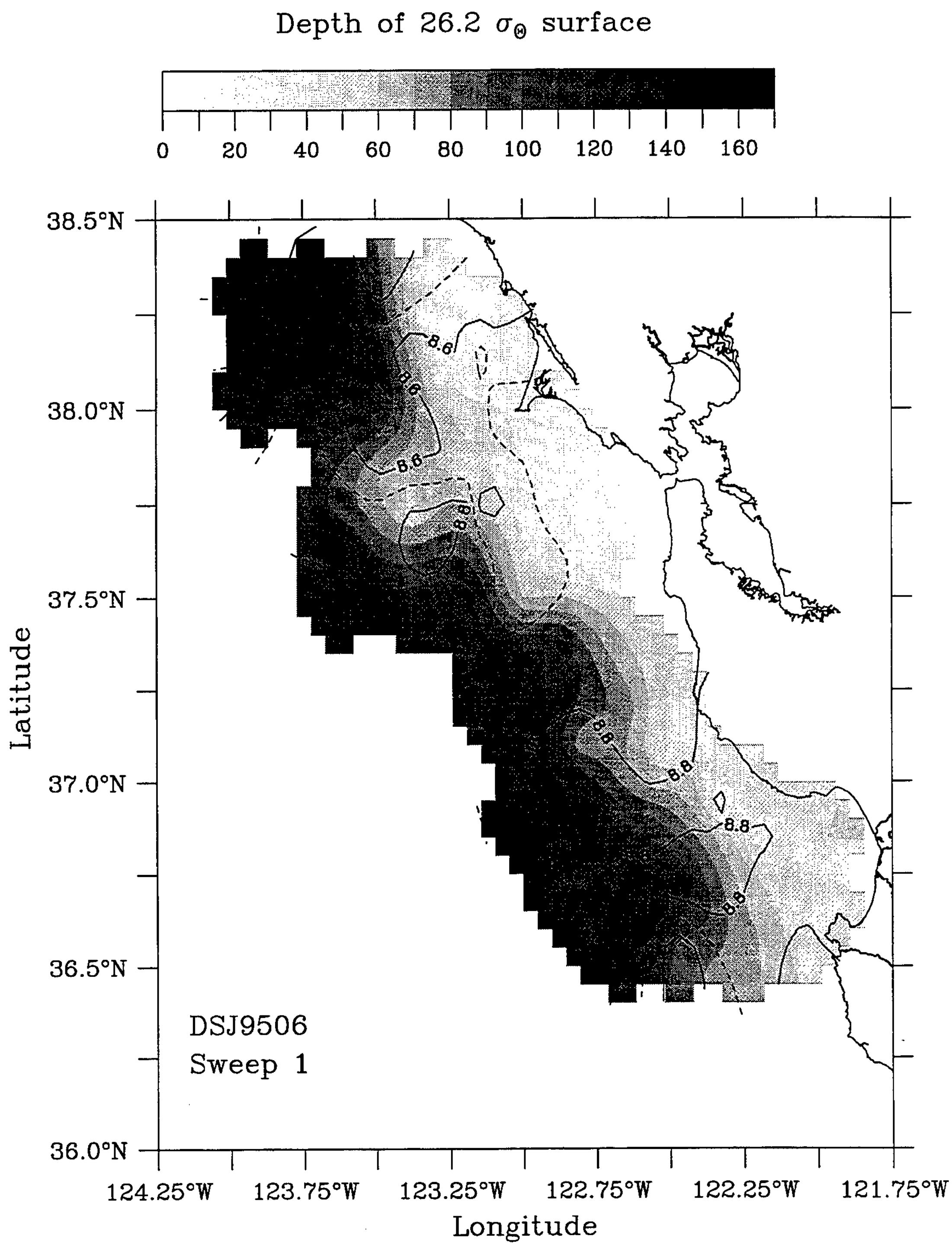
Similar to 1994, the 1995 spring-summer near-surface temperature and salinity fields were representative of an active coastal upwelling state. The sweep 2 data represent 1995 conditions (Fig. 22). Cooler and more saline water along the coast was concentrated near coastal promontories (Pt. Reyes, Pt Año Neuvo), generally inshore of warmer, fresher offshore water, separated by a frontal zone of steep gradients. Salinity in the upper 10 m was notably lower than in 1994, particularly during Sweep 1, the result of the increased runoff mentioned earlier. As in 1994, the coolest and most saline water originated north of the sampling area, near Pt. Reyes, extending into the Gulf of the Farallones. The Pt. Reyes filament again was evident at times, usually associated with an anticyclonic meander or eddy that extended seaward of the survey area. Another similarity between the 1994 and 1995 upwelling seasons was the cooling trend over the course of the surveys, particularly near Pt. Reyes and Pt. Año Neuvo. Cooler water at both promontories expanded offshore and equatorward through the season, in response to persistent upwelling-favorable winds. A warm and fresh meander developed off Monterey Bay in Sweep 3, as upwelling succeeded a two-day relaxation event. Observations of an anticyclone in this region have been documented under similar conditions (Rosenfeld et al., 1994).

During the DSJ9506 survey, the 26.2 isopycnal ranged in depth from 40 m onshelf to 130 m offshelf (Fig. 6). As in 1993 and 1994, the 26.2 isopycnal sloped up toward the coast in response to local upwelling during all three sweeps of 1995, as represented by the Sweep 1 map (Fig. 23). As seen in the previous two years, temperatures south of 37.50°N were more homogeneous than in the north. The warmest temperatures in 1995 (> 8.85°C) were confined to the southern part of the survey area, as seen in 1993. However, water on this surface was cooler and fresher relative to 1993, presumably due to the dissipation of the El Niño signal (i.e. a reduced contribution of water of a southerly origin). This surface deepened 30 m from the second to the third sweep near Point Reyes (38.00°N, 123.75°W), suggesting an onshore movement of less-dense offshore water (Fig. 24). Deepening was also evident



Temperature at 10m
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
16.0
38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
124.25°W
123.75°W
123.25°W
122.75°W
122.25°W
121.75°W
Longitude
DSJ9506
Sweep 2
33.6
33.2
32.8

Figure 22



Depth of 26.2 σ_θ surface
0
20
40
60
80
100
120
140
160
38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
124.25°W
123.75°W
123.25°W
122.75°W
122.25°W
121.75°W
Longitude
8.6
8.8
DSJ9506
Sweep 1

Figure 23

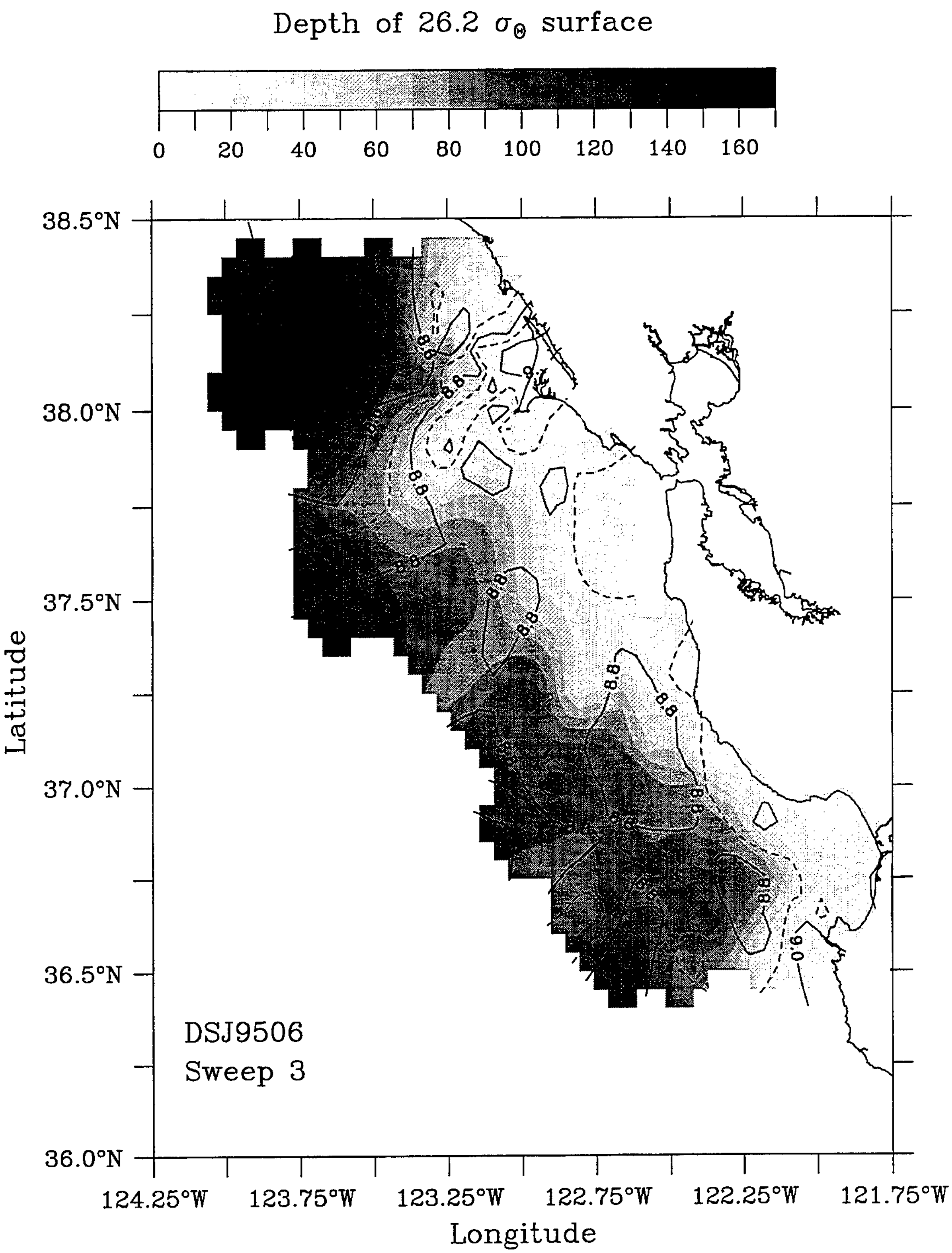

Depth of 26.2 σ_Θ surface
0
20
40
60
80
100
120
140
160
38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
124.25°W
123.75°W
123.25°W
122.75°W
122.25°W
121.75°W
Longitude
DSJ9506
Sweep 3
8.8
9.0

Figure 24

by the third sweep off Monterey Bay in response to the onshore advection of the warm, fresh meander.

As with 1994, currents during the 1995 upwelling season were generally disorganized, yet strong offshore and equatorward currents were associated with recently-upwelled water, evident in the first sweep (Fig. 25). Along the upwelling front, warmer, fresher water was observed flowing onshore and poleward adjacent to these upwelling filaments, and opposite the flow implied by geostrophy or local wind forcing. Another striking example of poleward flow was seen in Sweep 2 off Half Moon Bay (Fig. 26). Poleward and onshore currents of up to 40 cm/s were found south of the Pt. Reyes filament (36.50°N), during a period of persistent upwelling-favorable winds.

In all sweeps of DSJ9506, the Pt. Reyes filament flowed south and then offshore near 38.0°N as seen in the first sweep (Fig. 25). During the brief two day hiatus separating Sweeps 2 and 3, the northerly wind component was particularly strong and peaked at approximately 10 m/s (Fig. 21). Following this strong wind pulse, equatorward flow was particularly vigorous north of Pt. Reyes during the third sweep (up to 75 cm/s) (Fig. 27). The warm anticyclonic eddy off Monterey Bay was also observed in the third sweep of 1995. As with the two previous years, the presence of this feature coincided with a return to upwelling winds following a relaxation event (Fig. 21).

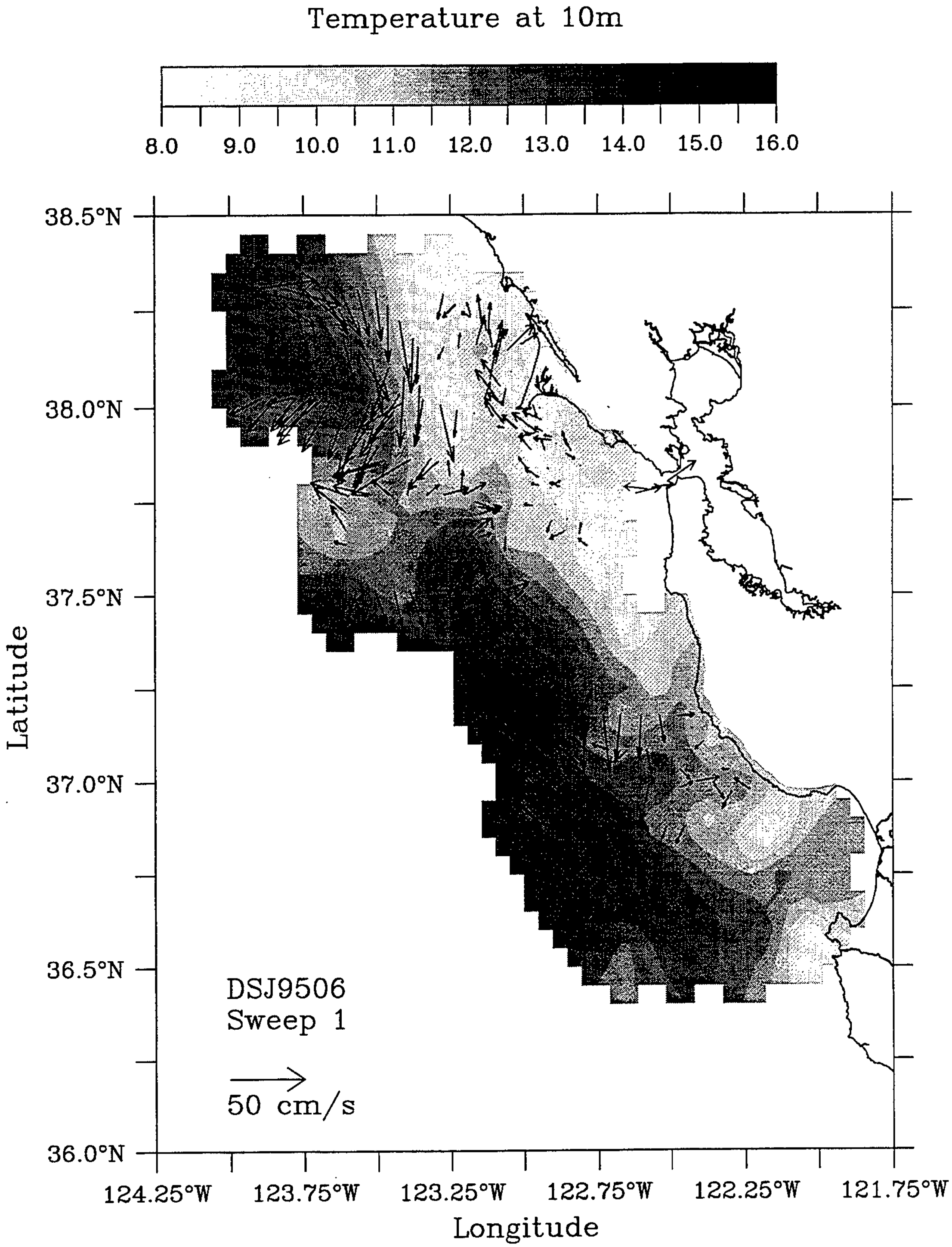

Temperature at 10m
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
16.0
38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
124.25°W
123.75°W
123.25°W
122.75°W
122.25°W
121.75°W
Longitude
DSJ9506
Sweep 1
50 cm/s

Figure 25

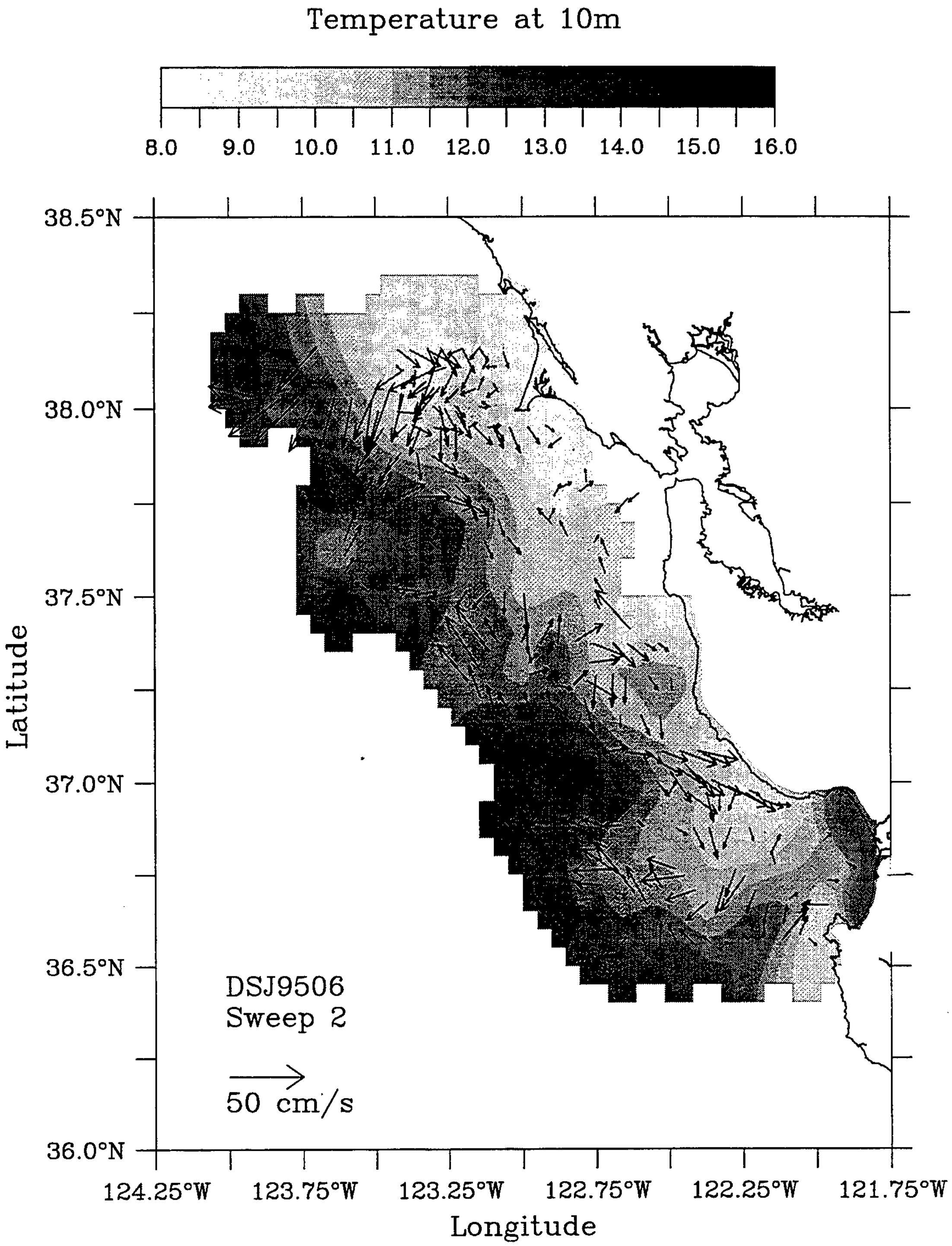

Temperature at 10m
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
16.0
38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
124.25°W
123.75°W
123.25°W
122.75°W
122.25°W
121.75°W
Longitude
DSJ9506
Sweep 2
50 cm/s

Figure 26

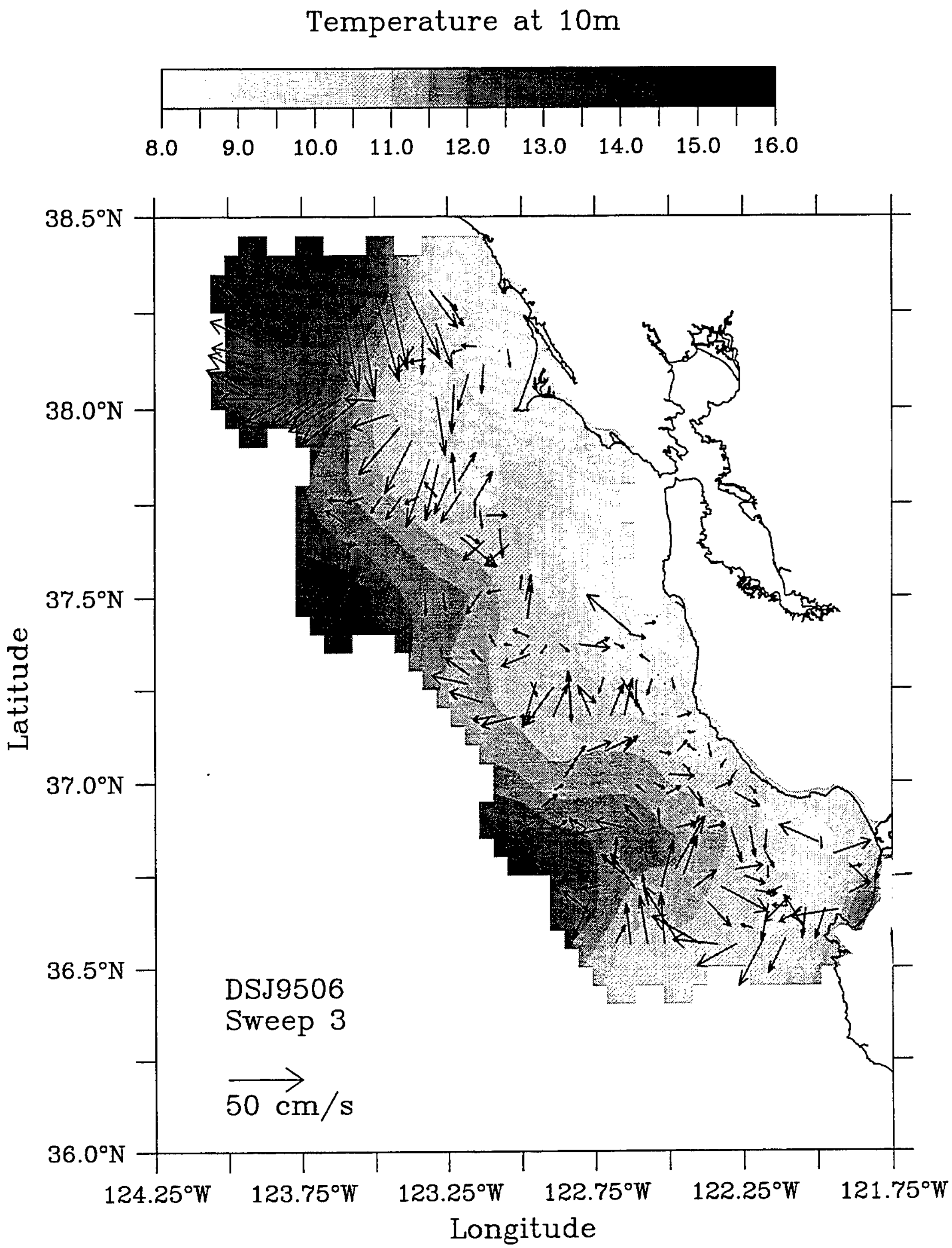

Temperature at 10m
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
16.0
38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
DSJ9506
Sweep 3
50 cm/s
124.25°W
123.75°W
123.25°W
122.75°W
122.25°W
121.75°W
Longitude

Figure 27

V. DISCUSSION

A. SPRING-SUMMER COASTAL CIRCULATION OFF CENTRAL CALIFORNIA

The high-spatial resolution NMFS data sets of both hydrographic and shipboard current measurements afford a perspective of the central California coastal circulation that supersedes previous geostrophic current estimates in this region. By examining variability within a season, through a contrast of three 10-day sweeps, and variability between three successive years, a clearer picture of the region's circulation pattern and its temporal variability emerges. Four particular circulation features recurred consistently in the upwelling seasons of 1993, 1994 and 1995. They are 1) the filament of recently upwelled water off Pt. Reyes, 2) the plume of recently upwelled water off Pt. Año Neuvo, 3) the anticyclonic flow off Monterey Bay, and 4) poleward and onshore currents along the upwelling frontal zone. Although varying in magnitude and location, these distinct features were generally present in all three sweeps of a given year, and in at least one sweep of each of the years surveyed. These features appear to define a distinct nearshore system separate from the California Current System and the processes that drive circulation within this distinct system. This type of nearshore system may be characteristic of coastal circulation at other locations in the California Current System and along other eastern boundaries, inshore of the principal equatorward current.

The Pt. Reyes filament was observed in each sweep of all three years. This feature is evidenced in the three-year mean ADCP near-surface currents (Fig. 28) by equatorward velocities of about 40 cm/s, from 38.5°N to 38.0°N, with an offshore flow just south of 38.0°N. During individual sweeps, the velocity core of this filament corresponded with relatively steep gradients of temperature and salinity and separated warm, fresh offshore water from colder, more saline recently upwelled water nearshore. The filament signal in the velocity field was evident to 100 m, with little vertical shear. As a high momentum current advecting cooler, saline water from the

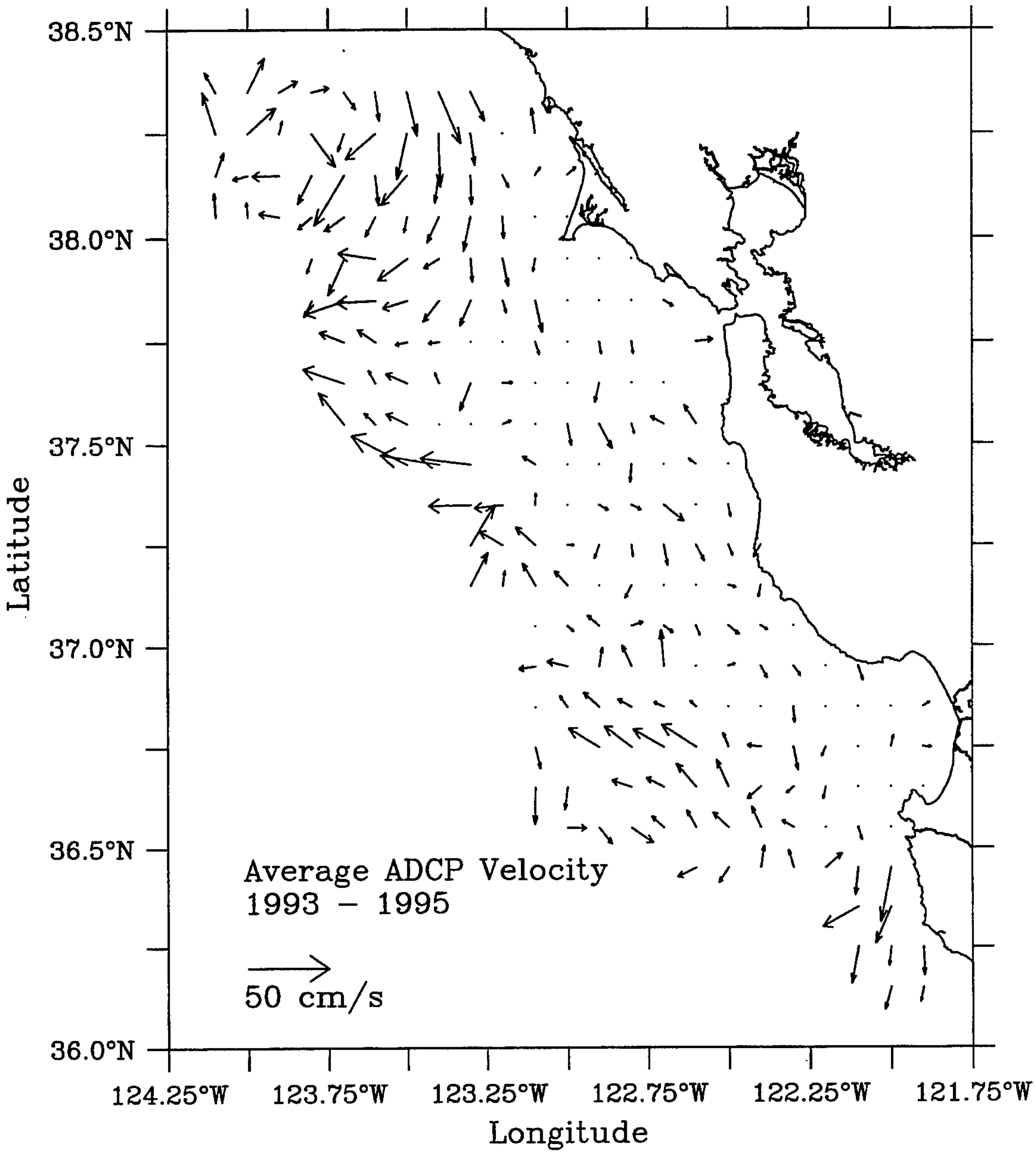

38.5°N
38.0°N
37.5°N
37.0°N
36.5°N
36.0°N
Latitude
124.25°W
123.75°W
123.25°W
122.75°W
122.25°W
121.75°W
Longitude
Average ADCP Velocity
1993 - 1995
50 cm/s

Figure 28

north, this filament provides a dynamic boundary that limits lateral mixing by its horizontal velocity shear. The vertical extent of the filament ensures that it is a fairly impenetrable barrier between this nearshore system and the California Current System. A general bifurcating trend into offshore and equatorward components is evident in AVHRR imagery (Figs. 18,19). The majority of the flow of the Pt. Reyes filament appears to be in the offshore branch, which was generally offshore of the NMFS survey area. The filament was present over a range of wind conditions, even during prolonged periods of downwelling-favorable wind, as seen in Sweep 1 of 1993 (Fig. 10). Thus the flow in the Pt. Reyes filament is not driven purely by variations in Ekman transport. This persistent filament could be driven by the local wind curl, or be due to a nonlinear response to the topography of the coastline in that region. However, the data set from the NMFS survey is not extensive enough to effectively examine the possible causes for its generation and persistence, as it did not sample the entire filament each sweep and each year.

Another circulation feature that recurs during the upwelling season is a cold and saline upwelling plume from Pt. Año Neuvo. It is similar to the Pt. Reyes upwelling filament in its water properties, and in the fact that both features are anchored to active upwelling centers and bifurcate as they move offshore. However, the Pt Año Neuvo plume responded differently to a wind field that was fairly uniform over the survey area. Unlike the larger Pt. Reyes filament, this relatively low-momentum feature occurred only during periods of prolonged upwelling winds. Its signal quickly dissipated as winds decreased. The difference in response of these two filaments to the synoptically-varying wind field supports the idea of Largier et al. (1993) of alongshore variation in response to upwelling-favorable winds, and may be linked to the variations in coastal topography between these two upwelling centers. The spatial and temporal variability of this feature account for its absence in the mean ADCP field (Fig. 28). When present in individual velocity fields, this filament did not penetrate much below 30 m depth, and was generally characterized by an equatorward current crossing the mouth of Monterey Bay. The offshore portion of this plume is generally seen most clearly in AVHRR imagery (Fig. 29). Rosenfeld et al. (1994)

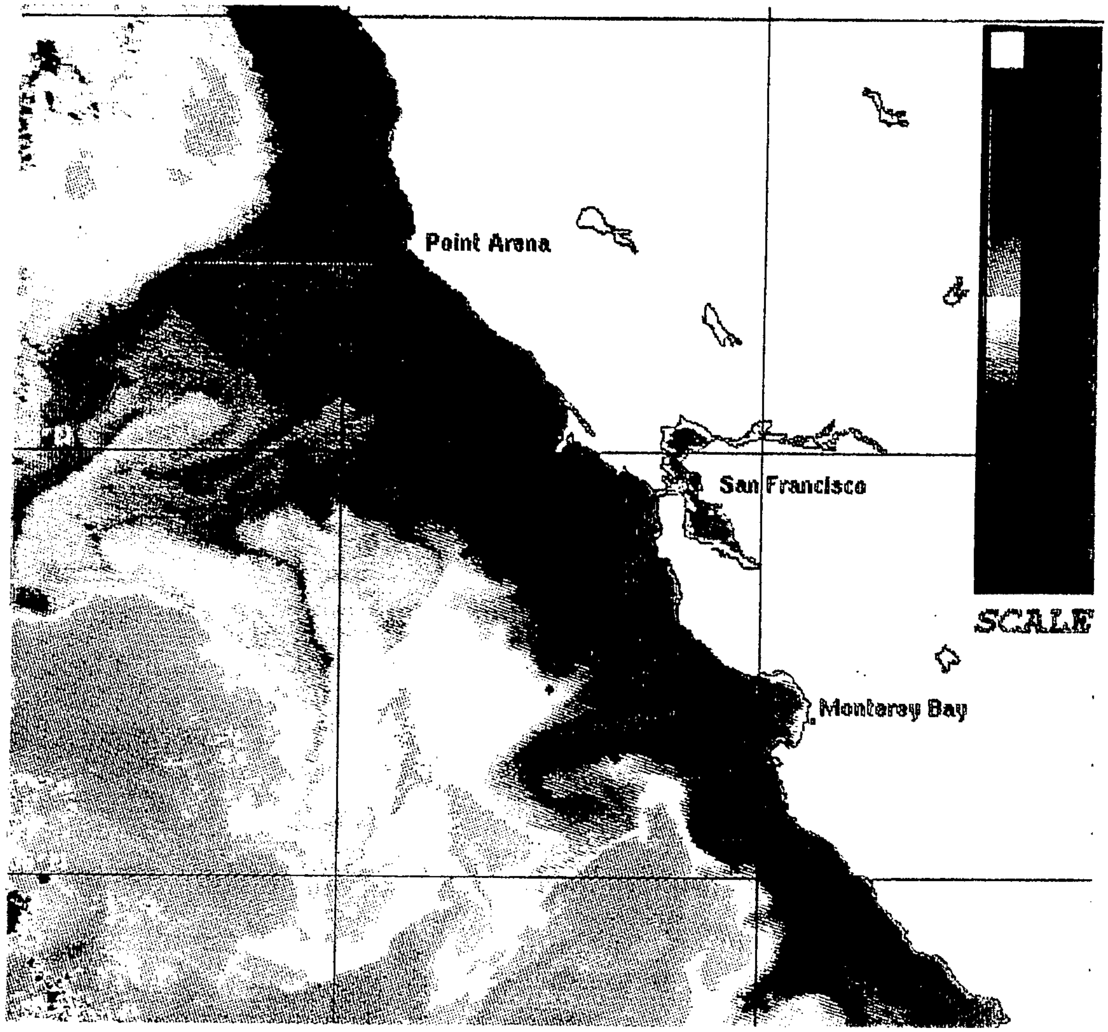


Figure 29

demonstrate that this filament is the source for cold, upwelled water in Monterey Bay.

The Pt. Año Neuvo upwelling center exhibits a classic Ekman response to wind stress along a coast, i.e., upwelling strengthening or relaxing in response to fluctuations in upwelling-favorable winds. The persistence and spatial extent of the Pt. Reyes upwelling filament indicates a more complex response at that upwelling center to virtually the same wind field found at Pt. Año Neuvo, highlighting a varied response by two nearby upwelling centers to a fairly uniform wind field.

Also found repeatedly in the upwelling season was an anticyclonic eddy or meander seaward of Monterey Bay. This warm and fresh feature was most evident in the current and hydrography fields at the onset of upwelling following a wind relaxation event. The temporal variability of this feature clouds its depiction in the mean ADCP field (Fig. 28). The recurrence of the anticyclonic eddy off Monterey Bay following a relaxation event supports the idea that relaxation from upwelling is driven by a combination of processes separate from those driving upwelling (Send et al., 1987; Rosenfeld et al., 1994). This anticyclonic flow, or "Monterey meander", is thought to be present in this region at times other than during the transition from relaxation to upwelling, usually offshore of the NMFS survey grid as a relatively warm meander. Evidence for this is found in subjective analysis of surface flow from a sequence of AVHRR images from the CTZ (Strub et al., 1991). It was also observed in a series of images from the summer of 1989 by Rosenfeld et al. (1994). Rosenfeld et al. (1994) ascribe its formation to the vorticity imparted by filaments of upwelled water from the Pt. Año Neuvo upwelling center to the north and from the Pt. Sur upwelling center south of Monterey Bay as they begin to move offshore in response to northwesterly winds.

A fourth, and somewhat unexpected, upwelling circulation feature found repeatedly in this region is the strong counterflow along the frontal zone between recently-upwelled water and offshore water. As filaments of dense upwelled water move rapidly offshore, they displace the warmer, fresher mixed water in this system. Mixed water in this region is most likely equivalent to the frontal water type defined in Schwing et al. (1991) as a linear mixture of offshore and upwelled waters.

Individual near-surface current fields reveal that this mixed water, historically considered quiescent, appears to respond to offshore-flowing filaments of upwelled water with a flow of roughly equal magnitude, in an opposite direction, as seen in Sweep 2 of 1995 (Fig. 26). Clearly evident in the mean ADCP near-surface flow, this return flow was most often observed between the Pt. Reyes filament and the meander/eddy off Monterey Bay (Fig. 28). These two persistent features appear to act as dynamic boundaries, essentially trapping the mixed water. This mixed water appears to flow around the recently-upwelled water features, while remaining within the confines of the system. Kelly and Strub (1992) found onshore and poleward return flow southeast of the Pt. Reyes upwelling filament in their feature-tracking of surface velocities from a sequence of AVHRR images. This strong return flow was also evident in in situ ADCP measurements and dynamic height calculations from the same period, and Kelly and Strub concluded that the offshore upwelling filaments in this region were interacting with a strong eddy field. Poleward and onshore velocities were also seen during upwelling-favorable wind conditions in May 1991 during the EPA-sponsored Gulf of Farallones circulation study (Ramp et al., 1995). The dynamics of the circulation in this area were considered the result of localized processes rather than by forcing from larger-scale California Current features. The poleward and onshore counterflows observed by others in this region sometime develop into eddies (Strub et al., 1991; Kelly and Strub, 1992). The formation of these eddies is linked to the meandering coastal jet and its associated larger-scale filaments that were characterized in the CTZ study. The anticyclonic eddy off Monterey Bay is smaller than these eddies, which are prevalent farther north and offshore of this region, and is most likely composed of mixed water from within this system, rather than water from an upwelling filament, or from water pinched off from the California Current.

The circulation in this system, while undergoing the synoptic fluctuations described above, was repeatable year to year in that the same general patterns were observed. The same was not true for the water masses or the density field. In 1994 and 1995, the depth of the 26.2 potential density (σ_θ) surface primarily ranged between

40-100 m, and along this surface most temperatures were between 8.5°- 8.9°C (Fig. 6). During the 1993 survey, an El Niño year, the 26.2 σ_θ surface was deeper, between about 60-150 m, and temperatures on this surface were warmer, typically about 9.0°C. The deepening of this surface could be due to the northward shift of water masses that has been observed during El Niño events (Lynn et al., 1995). A northward shift of about one degree of latitude could account for the observed change, and is in accord with model predictions.

To summarize, this nearshore system between Pt. Reyes and Cypress Point is distinct from the greater California Current, both geographically and dynamically. Its dynamic boundaries are the high momentum Pt. Reyes filament to the north and the Monterey meander to the south. The water types found within this system are recently-upwelled and a mixture of older-upwelled and offshore water. Water in this system seems to be retained within the boundaries, as exchange with the California Current is apparently limited. During upwelling-favorable winds, a low-momentum plume of upwelled water spreads from the Pt. Año Neuvo upwelling center, bifurcating into equatorward and offshore arms. The warmer, fresher mixed water in this system responds to displacement by the dense upwelled water with return flows of roughly equal magnitude, in the opposite direction, as seen in Sweep 2 of 1995 (Fig. 26). During active upwelling, the circulation patterns over the outer shelf and slope represent a relatively complex eddy field with patches of upwelled and mixed waters, separated by steep gradients or fronts. When upwelling-favorable winds are strong, horizontal shear caused by the rapid upwelling currents and their counterflows inhibits mixing. When upwelling-favorable winds weaken, production of the low momentum plume at the Pt. Año Neuvo upwelling center ceases and mixing and surface heating can occur. The high-momentum Pt. Reyes filament persists during relaxation events, despite the lack of upwelling-favorable winds. The Monterey meander generally translates onshore during a wind relaxation event, most likely due to an adjustment of the cross-shore pressure gradient established during the previous upwelling event. When upwelling-favorable winds return, the upwelling center at Pt. Año Neuvo becomes active again. The Monterey meander may form a discreet eddy as upwelling

resumes. Eddy formation in this case is presumably due to the mechanism described in Rosenfeld et al. (1994).

B. CIRCULATION VARIABILITY

Inspection of the three-year, nine-sweep mean ADCP current field does not fully represent the circulation pattern just described in this nearshore system. It represents only those features with particularly high velocities and with little spatial and temporal variability. As coastal circulation is constantly adjusting and never reaches steady state, it is important to characterize the variation from the mean state to fully understand a particular system.

The variability in this nearshore system is due primarily to the varied response of the Pt. Reyes and Pt. Año Neuvo upwelling centers to local wind forcing. At the Pt. Reyes upwelling center, a relatively high-momentum filament of upwelled water is observed throughout the upwelling season and in each year surveyed. This filament fluctuates in location and magnitude on a synoptic scale, yet these fluctuations do not appear linked to the wind field. In 1993, for example, the primary front, evidenced by steep temperature gradients between filament water and mixed water extended southwest from Pt. Reyes in Sweep 1 (Fig. 10). Ten days later, this boundary had shifted to south of the Golden Gate (Fig. 11) and after another ten days, the front was oriented parallel to the coast (Fig. 12). These fluctuations do not have any direct correlation with the local wind fluctuations (Fig. 2), which were predominantly poleward for the first two sweeps and returned to upwelling-favorable by the third sweep.

The response to upwelling-favorable winds at the Pt. Año Neuvo upwelling center is clearly different from that at the Pt. Reyes center. The high variability seen in the circulation at this location appears to be directly linked to synoptic wind fluctuations. The Pt. Año Neuvo upwelling plume is shallow and has relatively low momentum. When the driving force of this plume is removed or weakened, its signal quickly dissipates.

The significant variation in response to upwelling winds at these two upwelling centers may be related to the difference in the size and sharpness of each promontory. Pt. Reyes is a larger coastal headland than Pt. Año Neuvo, with a greater offshore extent. The implication is that this difference in coastline orientation could result in greater acceleration of local winds at Pt. Reyes, leading to greater wind curl and local upwelling. Variations in the degree of local upwelling do not appear to be the only cause for the different response observed at these two upwelling sites. The Pt. Reyes filament, as discussed earlier, continues to flow during relaxation events, while the Pt. Año Neuvo filament does not. The Pt. Reyes filament, then, must be generated and maintained by processes beyond local wind forcing, and processes beyond the scope of this study to determine.

The difference in bathymetry at these two upwelling centers may also influence the varied upwelling responses seen at Pt. Reyes and Pt. Año Neuvo. Approximately 35 km offshore of Pt. Reyes is a seamount, Cordell Bank. About 25 km south of Pt. Reyes are the Farallone Islands. These changes in bathymetry may promote a local convergence as the Pt. Reyes filament flows between them. As the filament converges, vorticity would increase to be conserved. This increase in vorticity would enhance cyclonic movement, and in essence "steer" the filament toward the equator. A local acceleration may also result from the constriction of the filament as it passes between these two high spots. Off Pt. Año Neuvo, the shelf and slope have a fairly constant grade, without the sharp disruptions seen off Pt. Reyes, thus the lack of local convergence at this upwelling center may be another cause for the different responses found at these two promontories.

The varied response of these upwelling centers may also affect the overall density structure in this nearshore system. Inspection of zonally-averaged temperature trends on the 26.2 potential density surface from 1993 and 1994 reveals regional differences in the year to year variations in water mass characteristics (Fig. 30). The system appears to be divided latitudinally into two distinct regions, separated at about 37.5°N. The distinction between the two regions is that in the south temperature is relatively homogenous, indicated by a smaller standard deviation of the zonally-

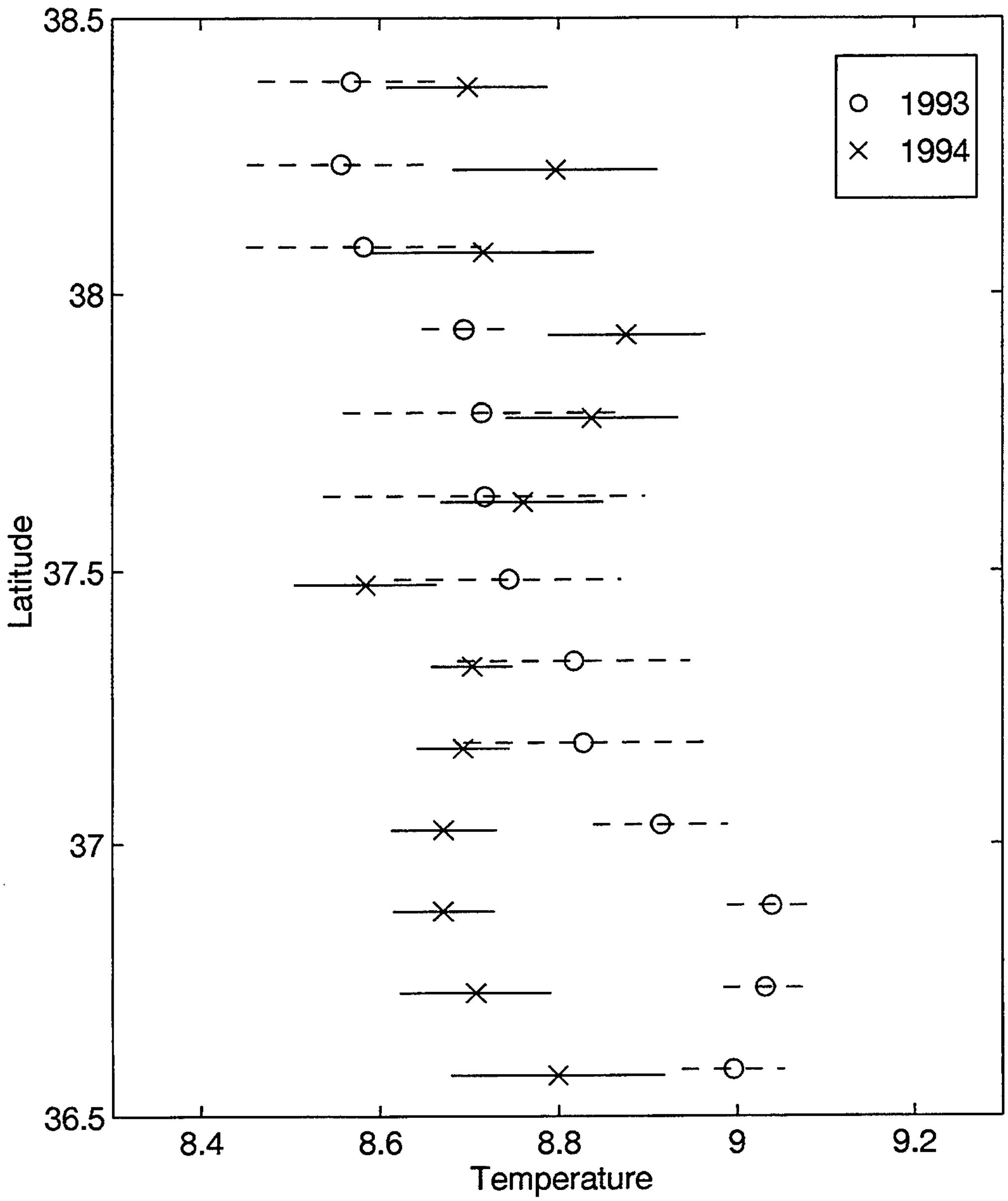


Figure 30

averaged temperature. In the north, temperature variability is greater. One possible reason for these observed differences is that the density structure in the north is dominated by the presence of the Pt. Reyes filament which is generally found to at least 100 m depth. The horizontal shear caused by the strong velocities of this feature may inhibit mixing of water types along density surfaces. Conversely, the ephemeral and relatively shallow Pt. Año Neuvo plume in the southern region does not appear to have a significant effect on mixing on density surfaces, particularly below 30 m.

C. CONCEPTUAL FLOW MODELS

Several conceptual models have been proposed recently for circulation off the California coast during the upwelling season. These models fall short of accurately describing the circulation in the area between Pt. Reyes and Cypress Point, inshore and separate from the California Current. Strub et al. (1991) developed three models to describe the structure of upwelling circulation, in particular, the evolution of filaments of upwelled water along the California coast. The first of these models involves squirts of cold, saline upwelled water generated by nearshore convergences. These squirts move rapidly offshore, transporting upwelled water, nutrients and biomass into the deep ocean in a one-way process. The nearshore convergences thought to generate these squirts are the result of alongshore variations in wind stress, presumably enhanced by local accelerations around coastal points. In the nearshore system studied by the NMFS survey, these squirts may occur episodically throughout the upwelling season, but do not typify the recurring circulation patterns discussed earlier. The lack of any strong return flow along these squirts is a primary discrepancy between this theory and the observed circulation. The Pt. Año Neuvo filament may be generated or enhanced by nearshore convergences, but the character of this feature as it moves offshore differs from the idealized squirt in that counterflows have been found associated with it, as in Sweep 2 of 1995 (Fig. 26).

A second model for upwelling circulation described by Strub et al. (1991) is a mesoscale eddy field moving slowly southward in a seasonal progression. As these

eddies randomly translate on and offshore, they are thought to draw cold, saline upwelled water away from the coast. The resulting filaments have properties similar to a squirt, but the eddy field in this model is responsible for creating these upwelled filaments. Offshore transport of temperature, nutrients and biomass occur by a slow, random process of eddy diffusivity. While mesoscale eddies are a recurring feature in the central California nearshore system, particularly the anticyclone off Monterey Bay, this model does not account for all the circulation patterns observed. The persistence of the Pt. Reyes filament when no eddy is present offshore implies that it is not generated by or closely linked to a mesoscale eddy. Likewise, there is no evidence in this survey that the Pt. Año Neuvo filament is generated by a mesoscale eddy. The length scale of the Monterey eddy is smaller than the length scale of the California Current, and its generation mechanism is likely different from that of the eddies in this CTZ model.

The third conceptual model of coastal circulation from Strub et al. (1991) is that of a baroclinic coastal jet that meanders on and offshore as it travels equatorward. Offshore meanders are thought to entrain recently upwelled water in dense filaments. Eddies form randomly along the jet, both offshore and inshore, presumably due to instabilities in the flow. The core of this jet contains water upwelled farther north. Squirts would not typically contain this water, but eddies would occasionally. The Pt. Reyes filament does transport water that was upwelled in the north. Another similarity between the meandering jet model and the circulation seen in this nearshore system is that water inshore of the jet is trapped there. In the nearshore system between Pt. Reyes and Cypress Point, it appears that upwelled water, and presumabley nutrients and biomass, are also retained within the boundaries of the system.

The mechanisms generating of squirts and eddies in the central California nearshore system may be similar to those in the Strub et al. (1991) models. There is no evidence in the NMFS data, though, that squirts and eddies are the vehicle for creating the upwelled filaments and plumes observed in this area. Strub et al. hypothesize that the meandering jet model is the dominant upwelling circulation mechanism off central California. While this theory is well-supported by extensive <u>in</u>

situ and remote observations of the greater California Current, this model does not explain the observed upwelling circulation inshore of the California Current. Again, the generation of the Pt. Reyes filament may be due to a mechanism similar to that described in the meandering jet theory, however, the NMFS survey did not sample extensively enough to accurately determine this mechanism. The CTZ meandering jet theory was developed for a specific region of the California coastline. It is not applicable to upwelling circulation to the south, between Pt. Reyes and Cypress Point.

The model of upwelling circulation developed in the NCCCS study claims that observed patterns are the result of higher-frequency (synoptic scale) wind fluctuations superimposed on more persistent, longer time scale, ocean-forced flow (Largier et al., 1993). Data from this study describes the seasonal progression of an alongshore pressure gradient that modulates current response to upwelling-favorable winds. On a period of weeks to months, mesoscale oceanic eddies translate onto the shelf and are also thought to influence flow by contributing to alongshore and cross shore pressure gradients. Despite these larger time scale influences, shelf currents in the NCCCS study were highly correlated with synoptic wind fluctuations. The response of currents to winds appeared to be influenced significantly by the effects of coastal topography on local winds. Upwelling was found to be enhanced immediately to the south of coastal promontories, and suppressed just to the north. The NMFS data set does not allow analysis of the seasonal progression of an alongshore pressure gradient. Alongshore variations in current response to wind fluctuations are evident in the NMFS data set, and are most likely related to changes in the coastal topography of this region. The influence of deep ocean mesoscale eddies on circulation patterns in this system is not clear. At times, the Pt. Reyes filament appeared to be closely associated with a mesoscale anticyclonic eddy that was just outside of the NMFS survey area, but sampling was insufficient to adequately assess the interaction between them. Unlike eddies in the NCCCS model, the Monterey meander does not appear to be of a deep ocean origin, but rather, evidence suggests that it is a locally-generated feature (Rosenfeld et al., 1994). The NCCCS model for coastal circulation during upwelling also fails to fully characterize the observed patterns in the NMFS survey

area. Larger-scale ocean forcing does not appear to play as great a role in the circulation in this coastal region as in the NCCCS survey area to the north.

A detailed characterization of upwelling circulation in the Monterey Bay region is found in Rosenfeld et al. (1994). Upwelling and relaxation states are defined as two separate processes with distinct dynamics, water characteristics and circulation features. The transition between the two is rapid. A typical observation of the prevailing upwelling state was the Pt. Año Neuvo filament, evident as cold, saline water crossing the mouth of Monterey Bay. During a wind relaxation event (i.e., a wind reduction or reversal), their model describes a rapid onshore advection of warmer and slightly fresher frontal water. In their model the Monterey meander is considered to be part of the California Current, translating onshore when upwelling winds relax. The return to upwelling-favorable winds is thought to enhance the development of this meander into a discreet eddy.

Observations from the 1993, 1994 and 1995 NMFS surveys support this idea as well. While the feature characterized by Rosenfeld et al. (1994) is likely the same feature that recurs throughout the NMFS study, the more recent data set implies that this water is not California Current water, nor is it closely coupled with the dynamics in the California Current. Their model presumes that the spacing of coastal points sets the length scale of upwelling centers and their filaments of upwelled water. These offshore filaments of upwelled water, anchored to the topographical points, act to reinforce the length scale of the meanders of the California Current. The nearshore system described by the NMFS data set includes very little data sampled directly from the California Current. It is unclear from this analysis what indirect effects the circulation within this system may have on the California Current itself. It does appear obvious that the alongshore length scale of upwelling filaments in this system is linked to the spacing of coastal points, as the two upwelling filaments seen repeatedly, Pt. Reyes and Pt. Año Neuvo, are anchored to the two most prominent coastal headlands.

The model for nearshore circulation that emerged from the NMFS study, then is unique from those described. The presence of a persistent upwelling filament

bounding intermittent upwelling centers establishes a system that promotes a productive ecosystem. The system is driven by the intermittent injections of nutrient-rich upwelled water and the dynamic boundaries create a dynamically closed system with a long residence time. This combination of different responses to upwelling conditions at upwelling sites creates pockets along an open coast where high productivity can occur.

VI. CONCLUSIONS

Several conceptual models exist that characterize circulation off the central California coast during the upwelling season. Yet these models, discussed earlier, do not fully explain the upwelling circulation observed in the nearshore (i.e., within 75 km of the coast) region between Pt. Reyes and Cypress Point. These models generally describe circulation in regions outside of the NMFS survey area, to the north or offshore in regions with less complex topography and bathymetry, focus on a larger spatial scale, or concentrate on upwelling near one upwelling center. Also, these models are based on surveys that do not have the high spatial resolution and temporal repeatability of the NMFS survey.

In addition to the dense spacing of stations and high degree of repetition, the NMFS survey was unique in that it involved collection of ship-based real-time current information as well as hydrographic data. The analysis of this rich data set has produced a conceptual model applicable to other eastern boundary current regions that may explain the presence of somewhat isolated regions of high productivity and biological diversity along an open coast. Our model defines a nearshore system inshore and separate from the principal equatorward current, with distinct water types and circulation patterns. Dynamic boundaries, such as a persistent upwelling filament and an anticyclonic meander, appear to be features of the principal current itself, enhanced by local winds, yet persistent despite wind fluctuations. There are two water types within this system, one is recently-upwelled water found along the coast, generally concentrated near sites of preferred upwelling (i.e., upwelling centers). The second type is mixed water, separated from recently upwelled water by steep gradients of temperature and salinity. Mixed water is a linear mixture of warm, fresh water from the principal current, or its coastal margin, that was closer to the coast before the spring transition to sustained upwelling conditions, and water upwelled at the coast of various ages. The resulting water has a signal that is distinct from the principal current water, yet is warmer and fresher than recently-upwelled water. Distribution of these water types is patchy throughout the region, since mixing and surface heating are

irregular and usually occur when upwelling winds diminish. When upwelling winds are strong, horizontal shear along filaments of upwelled water inhibits these processes.

During periods of sustained upwelling winds, water is upwelled within the system preferentially at coastal points or promontories. This cold, saline water will generally bifurcate into offshore and equatorward filaments. As this water moves rapidly away from upwelling centers, it displaces the less dense mixed water. Mixed water, constrained by the dynamic boundaries, responds to the intrusion by a counterflow of roughly equal speed in the opposite direction. This recirculation reduces exhcange with the greater California Current and promotes a long-residence time for water within the system. The implication for this long retention is that nutrients and biomass within the system also have a long residence time, enhancing the high degree of productivity and biological diversity usually associated with coastal upwelling regions.

In the nearshore system off central California, the observation of two significantly different responses by two distinct upwelling centers may be enhanced by the differences in the degrees of coastline orientation. It does appear that there are other processes at work that influence the response at the Pt. Reyes site that require further study.

Several questions about this system off central California remain for further study: what is the nature of the Pt. Reyes filament and what causes the response at this upwelling center to be so varied from the more typical response to upwelling winds at the Pt. Ano Neuvo site; what is the nature of the Monterey meander and what causes its persistence or recurrence. A more thorough, multi-disciplinary study including measurements of nutrients, chlorophyll and biomass would shed more light on the exact nature and cause of the long-residence time for water in these nearshore systems, and the implications for the productivity and diversity of ecosystems in this region. Comparisons with similar surveys for coastal regions of other eastern boundary systems would test the validity of this model for other nearshore regions.

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